AN ABSTRACT OF THE THESIS OF

Schyler Ainsworth Reis for the degree of Master of Science in Wildlife Science presented on March 17, 2017.

Title: Long-term Fuel Succession in the Sagebrush-steppe.

Abstract approved: ____

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Historically fire has been the primary disturbance factor in the sagebrush-steppe. The settlement of the West by Euro-Americans, grazing by domestic livestock, and the concomitant spread of invasive species have altered the historical fire regime. Understanding the long-term vegetation structure and fuel succession of the various sagebrush-dominated communities of this biome is important for managing the landscape in a way that will facilitate the complicated life histories of wildlife species of concern. The objectives of this study were to address the following current knowledge gaps: a lack of studies examining long-term post-fire fuel succession, a lack of studies that address repeated burns, and a lack of studies in basin big sagebrush (*Artemisia tridentata spp. tridentata)* and low sagebrush (*Artemisia arbuscula*).

To assess long-term fuels succession, the effects of repeated burns, and basin big and low sagebrush fuel structures, I conducted 2 different studies. I resampled previous fire effects studies where pre-fire and immediate post fire fuels data existed at Hart Mountain National Antelope Refuge (HMNAR), John Day Fossil Beds National Monument, Sheep Rock Unit (JODA), and on Prineville BLM land adjacent to Bear

Creek (BEAR). Two of these studies were conducted in basin big sagebrush communities (JODA, BEAR), and one of these studies had re-burned since the study's inception (JODA). The studies were designed so that fuel loads could be statistically tested and compared to their corresponding past studies. Fuels were first stratified into overstory and understory fuels. Overstory fuels consisted of all living and dead shrubs. Understory fuels consisted of downed wood (DWD); duff and shrub-related litter, bryophitic materials; and herbaceous fuels. Herbaceous fuels where then further divided into living grasses and forbs, standing dead grasses and forbs, and detached grass and forb litter.

In Wyoming big sagebrush communities at HMNAR that are now seventeen years post fire (YPF), overstory fuels only recovered to 13% of pre-fire levels and understory fuels only reached 25% of pre-fire levels. When compared to adjacent un-unburned control plots, the 17YPF plots had herbaceous fuels that were 5 times greater than controls (17YPF=154±20 kg ha^{-1}, controls=30.2±6 kg ha^{-1}; $P<0.01$). However, total fuel loads were >7x greater in unburned controls (6014.88±779.76 kg ha^{-1}) than in burned sites (831.2±192.8 kg ha^{-1}; $P<0.01$).

In contrast, in the Basin big sagebrush sites of BEAR and JODA, (25-26YPF) fuels recovered to 7-191% of pre fire levels (pre-fire, 36.2-16.8 Mg ha^{-1}; 25 years after fire, 69.1-2.3 Mg ha^{-1} [BEAR]), and to 113-209% (pre-fire, 6.2 Mg ha^{-1}; 26 years after fire, 13.0-7.1 Mg ha^{-1}[JODA]). Repeated burns at JODA significantly altered fuels composition. Fifteen years post a single fire (15YPF), herbaceous fuels made up 44%, and shrubs were 39% of total fuels. The fuel loads (aboveground biomass) of twice-burned sites (2xB;burned 26 years *and* 15 years prior) had a composition of 71%

herbaceous and 12% shrub mass. Total fuel loads in 15YPF and 2xB sites ranged from 3.5-6.0 Mg ha^{-1} and did not differ by site (*P*=0.85).

Sites from these study all showed high levels of resilience to disturbance by fire, with none of them converting to an alternative state dominated by invasive annual grasses. This is encouraging, and managers and scientists interested in exploring the use of fire as a tool to manage sagebrush steppe ecosystems in a way creates a mosaic of various habitats and fuel loads can use results from this study to facilitate their specific needs.

Long-Term Fuel Succession in the Sagebrush-steppe

by
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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented March 17, 2017
Commencement June 2017

Master of Science thesis of Schyler Ainsworth Reis presented on March 17, 2017

APPROVED:

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Schyler Ainsworth Reis, Author

ACKNOWLEDGEMENTS

My appreciation for those who helped me and contributed to this thesis could not be more sincere. Firstly I must express my deepest thanks to my advisors J. Boone Kauffman and Lisa M. Ellsworth. Their combined interest in my success has been transformative in my life. I would also like to thank Ricardo Mata-González for serving on my committee. I received writing instruction from Viki Burton. Jake Dittel assisted in the statistical analysis and R-studio programing. Dana Sanchez provided advice about this project and graduate school. Thank you to Joint Fire Science for funding this project (project #14-1-02-5), and thank you to Lisa and Boone for securing this funding. Thank you to the Greater Sheldon-Hart conservation fund, Thank you to Jeff Mackay for the BBQ'd steelhead. Thank you to the staff and managers of Hart Mt. National Antelope Refuge, John Day Fossil beds and the Prineville BLM. Thank you to the University of Nevada, Reno, sage-grouse crew. I would like to Levi Jaster, Philip Street, and Tessa Behnke. I would like to thank the entire Kauffman and Ellsworth families, including their pets. Thank you to Ruth Johns. I would like to thank the collaborating scientists: Dave Wrobleski, Bill Pyle, and Dave Sapsis. Also, thank you Dave and Arleen Sapsis for inviting me into your home in Sacramento. Thank you to all of the field technicians that helped with data collection: Cimarron Kauffman, Bobby Burdick, Emily Love Platte, Neil Rosenquist, and Lauren Christy. Thank you to Emily and Jeremy and all of the other musicians at Hart Mt. Thank you to Scott Heppell for allowing me to dry samples in your ovens. Thank you to all the other fish and wildlife graduates with whom I commiserated. Thank you Dean Olson. Thank you to all of my friends for your understanding about my busy schedule. Thank you Brynn Grossman for helping me by proof reading and editing my drafts. Especially I need to thank my family. Amah and Ampah thank you for your support and interest in my projects. Mom, thank you for your love, understanding, and support. Victoria, thank you for being such a positive role model and an intellectual sparring partner. Samimi thank you for being my niece. Forest, thank you for letting me use your bedroom when I visit, since Mom and Dad turned my bedroom back into the computer room. Mostly of all, thank you Dad (Jeff Reis) for being so strong and supportive. After you had your stroke on Christmas day, 2014,we were in the hospital, you and could barely communicate, but you told me to never give up, to never quit, to finish my degree. You know what it takes; you have never quit in your life. You are the toughest person I have ever met, and I have met some pretty tough folks, including five time UFC champion Randy Couture.

CONTRIBUTION OF AUTHORS

My advisors Lisa Ellsworth and J. Boone Kaufman assisted in the study design, data collection and analysis, and editing of all chapters of this thesis. They also acquired the funding for this project. David Wrobleski, David Sapsis, and Bill Pyle assisted by providing previous data sets, and in the location of old study plots.

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CHAPTER 1: INTRODUCTION TO THE THESIS

The Sagebrush Steppe

The sagebrush steppe ecoregion is widespread across the western United States, occurring in parts of Washington, Oregon, California, Idaho, Montana, Wyoming, Colorado, Utah, and Nevada (Kuchler, 1964, 1970). However, it currently occupies approximately 60% (214,000 km^2) of its historic range (360,000 km^2; Miller et al., 2011). This decline is due to many factors that continue to threaten the ecoregion including land development and the synergetic effects of overgrazing, invasive species, and altered fire regimes (Crawford et al., 2004; Miller et al., 2011; Miller and Eddleman, 2001; Shultz, 2012).

Fire was historically the primary disturbance in the sagebrush steppe. Fires in sagebrush are usually stand-replacing, killing and consuming most aboveground biomass wherever the fire burns (Sapsis 1990). The spread of fire across the landscape can be highly variable, and is dependent on amount and compositions of available fuels (Beardall and Sylvester, 1976). This variable spread of fire across the landscape of the sagebrush steppe perpetuates a matrix of various successional stages and is important for the persistence of sagebrush obligate species like the Greater sage-grouse (*Centrocercus urophasianus*; Gregg, 2006) and the ecosystem itself (Miller et al., 2013). On a small scale, fire is driven by the chemical reaction of combustion and can be represented by a fire triangle composed of oxygen, heat, and fuel, where fuel can be defined as any aboveground biomass capable of combustion in a fire (Pyne, 1984). On a larger scale, the behavior of a fire can also be represented by a triangle - composed of weather, topography and fuel (Pyne, 1984). Because fuels play such a critical role in fire on multiple scales, and fire plays such a critical role in successional matrix of sagebrush steppe communities, developing a long-term and detailed understanding of the dynamics and succession of how fuels return to various sagebrush steppe communities after fire is critical in advancing the conservation and management of this widespread and at risk ecosystem.

Sagebrush Steppe Ecosystems, Communities, and Sagebrush Species

Sagebrush steppe ecosystems are typically co-dominated by perennial bunchgrasses and sagebrush (*Artemisia spp.*; Figure 1.1), which occupy some of the harshest sites in North America—sites that are too dry to support forests and either too cold or wet to support the other shrubs or succulents that typically dominate warm deserts (Shultz 2009). Big sagebrush (*Artemisia tridentata*) is the most common species of sagebrush and has three subspecies: basin (spp. *tridentata*), Wyoming (spp. *wyomingensis*), and mountain (spp. *vaseyana*; Shultz, 2012). These subspecies are adapted to specific habitats (Shultz, 2009) along temperature, moisture, soil, elevation, productivity, and fire return interval gradients (Miller et al., 2013). The sagebrush steppe range is bordered at its hot and dry, low-elevation end by salt-desert and desert shrub plant communities, and at its cool and wet, high-elevation end by western juniper (*Juniperus occidentalis)* communities (Miller et al., 2013).

Wyoming big sagebrush communities occur at the warmer and drier, lower elevation end of the sagebrush steppe. They occupy sites with elevation ranges of 150m-1,200m (Miller and Eddleman, 2001) with an annual precipitation between 18 and 30cm (Mahalovic and McArthur, 2004; Miller and Eddleman, 2001; Shultz ,2009), and on soils that often contain argillic, caliche, or silica layers (Miller et al., 2011). Wyoming big sagebrush covers the most land area of the big sagebrush subspecies (Miller and Eddleman, 2001; Tisdale, 1994). In Wyoming big sagebrush communities, common associated bunchgrasses are bluebunch wheatgrass (*Pseudoroegneria spicata*), western wheatgrass (*Pascopyrum smithii*), Sandberg bluegrass (*Poa secunda*), bottlebrush squirreltail (*Elymus elymoides*), Idaho fescue (*Festuca idahoensis*), Thurber needlegrass (*Achnatherum thurberianum*), and needle-and-thread grass (*Hesperostipa comata*) (Howard, 1999). Wright and Baily (1982) and Mensing (2006) report a mean fire return interval, or the average time in years between fire events in a specified area of interest (Miller et al., 2013) to be 50-100 years, based on recovery rates of sagebrush and macroscopic charcoal records. Baker (2006) believes Wyoming big sagebrush communities burn less frequently and reports a fire rotation, or the length of time required for an entire area of interest to burn to be 100-240 years. Baker (2006) also defines fire rotation to usually be two or more times the recovery period, so actually numbers reported by Baker (2006) and Wright and Bailey (1982) are not as different as they seem.

Mountain big sagebrush communities occur on cooler sites than Wyoming big sagebrush. They are typically found in foothill and mountain areas consisting of moderate to deep well drained soils with elevations of 1,200 to 3,100m and with an annual precipitation from 35 to 45cm. In the ecotone between Wyoming big sagebrush and mountain big sagebrush communities, the two sagebrush subspecies can hybridize into what is known as Bonneville sagebrush (Shultz, 2012).

Mountain shrub communities are located at the most mesic end of the sagebrush community spectrum. They consist of mountain big sagebrush co-dominated by several other shrubby plant species including antelope bitterbrush (*Purshia tridentata*), snowberry (*Symphoricarpos spp*.), serviceberry (*Amelanchier alnifolia*), and mountain mahogany (*Cercocarpus spp*.) among others. Annual precipitation rates in these communities are at least 40cm (Miller et al., 2013). Common grasses associated with sagebrush communities dominated by Mountain big sagebrush include Idaho fescue, bottlebrush squirreltail, bluebunch wheatgrass, Sandberg bluegrass, Kentucky bluegrass (*Poa pratensis*), and basin wildrye (*Leymus cinereus*; Johnson, 2000).

Communities where the dominant sagebrush species is mountain big sagebrush often recover to preburn levels in 20-35 years, though recovery can take up to 50 years in some areas (Miller et al., 2013). A fire return interval of 40-50 years is required to prevent these ecosystems from being encroached by western juniper (Burkhart and Tisdale, 1976). In the Chewuacan River basin between 1601-1871, Miller and Rose (1999) found the time between fire events to range from 12-15 years, Others suggest a general fire return interval for this ecosystem of 15-25 years (Burkhardt and Tisdale, 1976, Miller and Heyerdahl, 2008, Miller et al., 2011).

Basin big sagebrush (*Artemesia tridentata* spp. *tridentata*) grow in well-drained, sandy, deep soils of valley bottoms, in fertile, deep soil pockets of mountain slopes, and along roadways and fence rows (Tirmenstein, 1999; Shultz, 2009) in areas that receive 25-50 cm of precipitation per year (Tisdale, 1994). It is the tallest of all big sagebrush subspecies, and it is not uncommon for it to reach 2 to 3 meters in height (Shultz, 2012) with a maximum recorded height of 5 meters (Wright and Baily, 1984). Because basin big sagebrush naturally occupies territory with fertile soil, by the start of the 20th century, Euro-American settlers had converted most areas previously dominated by basin big sagebrush into agricultural land uses (Shultz, 2012). Bunchgrasses commonly associated with Basin big sagebrush include bluebunch wheatgrass, Thurber's needlegrass, needle-and-thread grass, Idaho fescue, and Sandberg bluegrass (Tirmenstein,1999). The fire return interval for basin big sagebrush has been hypothesized to be either an intermediate between Wyoming big sagebrush and mountain big sagebrush (Sapsis,1990), or more frequent than that of both other sub species (Lesica et al., 2007).

Grazing, invasive species, and altered fire regimes

The plant communities that occupy the sagebrush steppe and surrounding ecosystems evolved with fire but not under heavy grazing pressure (Mack and Thompson, 1982), and benefit from fire related disturbance patterns (Kauffman et al., 1997; Wrobleski and Kauffman 2003). The perennial bunchgrasses that co-dominate the sagebrush steppe are fire-tolerant, surviving and reproducing post-fire in un-grazed mountain big sagebrush communities (Ellsworth and Kauffman, 2010). However, the bunchgrasses that co-dominate the sagebrush steppe did not evolve under heavy grazing pressure by American bison (*Bison bison)* like the prairies and grasslands east of the Rocky Mountains (Mack and Thompson, 1982). Over 70% of the western United States is currently grazed by domestic livestock, making grazing the most widespread land use practice in the western United States (Fleishner, 1994). Cattle grazing affects fire regimes in the sagebrush steppe directly by altering total and fine fuels, disrupting fuel continuity (Davies et al., 2010), and indirectly by altering plant community composition through preferential grazing and through the spread and facilitation of invasion of exotic annual species (Miller et al.1994). Overgrazing by domestic livestock will alter bunchgrass structure and abundance and reduce the biological soil crusts which occupy the interspace between shrubs and bunchgrasses, leading to an increase in size and connectivity of bare soil and a loss in inherent site resistance to invasion from alien annual grasses (Reisner et al., 2013).

The introduction of livestock and the concomitant invasion of exotic annual grasses, increased human ignition sources, and active fire suppression have altered the fire regimes of sagebrush steppe ecosystems (Miller et al., 2013; Miller and Eddleman, 2001; Westoby et al., 1989). Invasion by exotic annual grasses and grazing has fundamentally altered fire regimes of sagebrush communities, affecting frequency, intensity, extent, type, and seasonality of fire (Brooks et al., 2004). The fine fuels contributed by cheatgrass (*Bromus tectorum)* and other invasive annual grasses—which readily invade overgrazed areas of rangeland (Miller et al., 2013) promote fire by increasing horizontal fuel continuity and the fuel surface-to-volume ratio, and by creating a fuel-packing ratio that facilitates ignition (Brooks et al., 2004). This alteration of fuels can generate a positive feedback loop that results in cycles of invasion and repeated burns, where fire facilitates invasion and invasion facilitates fire (Brooks et al., 2004; Chambers, 2014), and can shift the ecosystem to an alternative stable state of annual grass dominance (Miller et al., 2013; Miller and Eddleman, 2001; Westoby et al.,1989). For instance, in the Snake River Plain, Idaho, fire-return intervals have been reduced from 50-100 years to <10 years due to cheatgrass invasion and the presence of human ignition sources (Whisenant, 1990). Cheatgrass-fueled wildfires were also disproportionately larger than those in native plant communities (Balch et al., 2013).

The higher elevation, cooler, wetter sagebrush communities (mountain big and mountain shrub) are at risk from encroachment by conifers (e.g., Western Juniper [*Juniperus occidentalis*]) that are expanding into sagebrush steppe ecosystems at a rate that is unprecedented for the last 6,000 years (Miller and Wigand, 1994). This phenomenon is believed to be the result of fire suppression practices of Euro-American settlers, favorable climate conditions during the little ice age (approximately 1300-1870 AD; Burkhardt and Tisdale, 1976), as well as increased atmospheric CO_2 levels (Knapp and Soule, 1996). This expansion is also happening in a time of drier and hotter climatic conditions compared to that of the pre-settlement times, when conditions of expansion were cooler and wetter (Miller and Rose, 1999). A fire return interval of <50 years is reported as adequate to prevent juniper encroachment into these sagebrush communities (Burkhardt and Tisdale, 1976).

Post-fire succession

Although post-fire plant community succession is highly dependent on pre-fire plant community composition, environmental conditions and conditions related to the fire itself (season of burn, intensity of burn, area of burn, post burn management), there is a general chronology for post-fire plant community response (Miller et al., 2013). Fires in sagebrush ecosystems can be high intensity and severity (Sapsis, 1990) killing and consuming entire stands of sagebrush (Blaisdell,1953; Miller et al., 2013; Figure 1.2). Because sagebrush does not resprout post-fire (Shultz, 2012) sufficient time and favorable climate conditions (Maier et al., 2001) are required for sagebrush to reestablish within the fire perimeter, either from seeds driven by the wind (Mueggler, 1956) from shrubs on the fire perimeter or unburned islands, or from seeds banked in the soil

(Johnson and Payne 1968; Miller et al., 2013; Mugger, 1956; Ziegenhagen and Miller, 2009). In the meantime, the burned area will be dominated by annual grasses, re-sprouting bunchgrasses and re-sprouting shrubs like rabbitbrush (*Ericameria spp.)* and horsebrush (*Tetradymia spp*.; Miller 2013 et al.; Figures 1.3 and 1.4). The amount of time required to reach sagebrush dominance is highly variable between and within big sagebrush subspecies, but it is believed that mountain big sagebrush recovers to pre-fire levels between 20-50 years post-fire (Miller et al., 2013) and that Wyoming big sagebrush recovers at a slower rate, requiring between 30-120 years to reach pre-fire cover levels (Baker, 2006; Watts and Wambolt, 1996). The rate of sagebrush recovery can be dependent on post-fire precipitation levels (Maier et al., 2001), the complexity of the unburned matrix with in the fire perimeter, and the number of sagebrush seeds in the soil that survived the fire (Zeigenhagen and Miller, 2009; Figures 1.5 and 1.6), and the effects of repeated burns (Chapter 3 of this thesis). After sagebrush reach dominance (Figure 1.7) it is possible for stands of sagebrush to suppress the understory forbs and bunchgrasses (Figure 1.8; see Ellsworth et al., 2016). If a fire occurs once this state of suppressed understory is reached, or if there are repeated fires without adequate time for sagebrush, bunchgrass, and the native forb components to recover, it can lead to a shift to an alternative stable state of annual grass dominance (Miller et al., 2013; Figures 1.9 and 1.10).

A Long-Term Perspective on Fire Regimes

The above successional trajectory describes relatively intact and undisturbed sites. Over the past 10,000-12,000 years the fire regimes of the sagebrush steppe have been dynamic, shifting over time in elevation, area, and abundance as the climate conditions changed. Fires were more frequent during wetter climatic conditions when fuels were more abundant (Mensing et al., 2006). However, since Euro-American settlement in the mid-nineteenth century, changes in plant composition have occurred at unprecedented rates. This is likely a result of the introduction of cattle, sheep, and horses, the concomitant introduction of alien plant species, alteration of fire regimes, land use change, and anthropogenic climate change (Miller et al., 1994).

Prior to Euro-American settlement, Native Americans in the sagebrush steppe and surrounding areas frequently used fire as a management tool to alter plant communities and manage game habitat and movement. This practice of frequent, low-intensity fires resulted in a landscape mosaic of varying successional stages (McAdoo et al., 2013). McAdoo et al. (2013) concludes that sagebrush ecosystems—including the arid and relatively low productivity Wyoming big sagebrush communities—would readily have adequate fuels to burn more frequently then every 70 years, even in the absence of cheatgrass. Developing a better understanding of the dynamics of long-term post-fire fuels succession in un-grazed, relatively intact sagebrush ecosystems will provide much needed information on the fire frequency and fire regime of pre-settlement, pre-grazed sagebrush ecosystems, the conditions that these communities evolved, and the conditions in which they should be the most resilient. However, this is particularly challenging because less than 1% of sagebrush steppe remains unaffected by livestock (West, 1999). Nonetheless, understanding the pre-European settlement disturbance regimes and plant communities of the sagebrush steppe and its relation to current conditions and management is an important component for restoration and sustainable management (McAdoo et al., 2013), and can help inform land managers how to best address the current and likely future disturbance regime related management decisions. There is a paucity of long-term fire studies in sagebrush ecosystems (Miller et al., 2013), and very few have examined the fuel dynamics over the long-term. This can be particularly difficult because the time-frame of sagebrush succession often exceeds the careers or even the life spans of those who study it (Morris and Leger, 2016).

The fuels in the sagebrush steppe include duff, grass, herbs, downed wood, shrubs, and trees (Byram, 1959). Often fuels are characterized into types by the general structural characteristics of the vegetation of the ecosystem and are then further delineated by their vertical layering, (e.g. ground, surface, or canopy fuels; Brooks, 2004). Within sagebrush dominated ecosystems, some studies have divided fuels into only two categories (*e.g.* overstory and understory fuels; Wrobleski,1999). Some (Bates et al., 2009; Davies and Bates, 2010; Davies et al., 2010; Hanna and Fulgham 2015; Kauffman and Cummings, 1989; Kauffman et al., 2006; Sapsis,1990) further subdivide fuels into as many as six categories that are inconsistent across studies.

The amount (loading) and types of fuel and their relative proportions are critical in predicting and modeling fire behavior and planning strategies for active fire suppression (Brown, 1982). Brown (1982) found that litter and grass were important fuel components when modeling fire behavior and rate of spread. Brown (1982) found that 773 kg ha^{-1} of litter fuel was the minimum amount required to facilitate fire spread in big sagebrush during prescribed burns that often take place during weather conditions that facilitate controlling the fire. Britton and Clark (1985) found that 20% canopy cover of sagebrush and 300 kg ha^{-1} of herbaceous fuel was needed to carry fire in prescribed burns. For fire spread, high herbaceous fuel loads (approximately 1000 kg ha^{-1}) are required when shrub canopy is low (approximately 10% cover) but on sites with high shrub cover (>20%), less herbaceous fuel loads (<300 kg ha^{-1}) are required. Beardall and Sylvester (1976) proposed that 670 kg ha^{-1} of herbaceous fuel was needed in big sagebrush for prescribed fire to spread.

Although there are few studies that examine the dynamics of fuels accumulation over time in sagebrush dominated ecosystems, there are several studies (Harniss and Murray,1973; Wambolt and Payne,1986; Watts and Wambolt, 1996) and meta-analyses (Baker 2011; Wambolt et al. 2001) that measure sagebrush recovery (in terms of percent cover) over time, post-fire, and post mechanical and chemical treatment. For example, Harniss and Murray (1973) monitored long-term (1936-1966) post-fire vegetation recovery of a site near Dubois, Idaho, and observed quick recovery of total forbs and grasses, which exceeded pre-fire levels within 3 years post-fire. Rabbitbrush and horsebrush exceeded pre-fire levels from 3 years post-fire, until up to 30 years post-fire, and big sagebrush recovered slower, but reaching 86% of pre-fire levels at 30 years post-fire.

Miller et al. (2013) stated that the collective understanding of fire effects in sagebrush-dominated ecosystems is severely lacking in several respects: 1) there is a deficit of long-term fire studies (>10 years); 2) there is a need for studies that examine the effects of repeated burns; and 3) there is a lack of studies focusing on basin big sagebrush ecosystems. I directly address these issues by resampling three fire effects studies that were originally conducted more than 10 years prior, some which were located in understudied sagebrush communities and one that has since re-burned. Developing a better understanding of long term fuel recovery in various sagebrush communities will lead to a more comprehensive understanding of future fire behavior and ecosystem resilience, in turn, providing fire managers, those concerned with wildlife conservation, and rangeland managers an additional tool to accomplish fire related management objectives.

Chapter 2 examines the recovery of Wyoming big sagebrush and the changes in its total fuels and composition 17 years following fire at Hart Mountain National Antelope Refuge in Oregon. Chapter 3 explores recovery and fuel succession in basin big sagebrush (*Artemisia tridentata* ssp. *tridentata*) communities as well as the effects of repeated burns 26 years after fire at Bear Creek, Oregon, and at the Sheep Rock Unit in John Day Fossil Beds National Monument in Oregon.

Collectively, the data presented significantly advances the understanding of how the dynamics and succession of fuel loads and fuel composition vary with time since fire and by sagebrush community type. This information will be critically useful for private landowners and land managers concerned with the matrix of seral stages of sagebrush necessary for viable habitat for sagebrush obligate species, will aid in future fire modeling efforts, and increase the overall understanding of fuels dynamics in these fire-adapted ecosystems.

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TABLES AND FIGURES

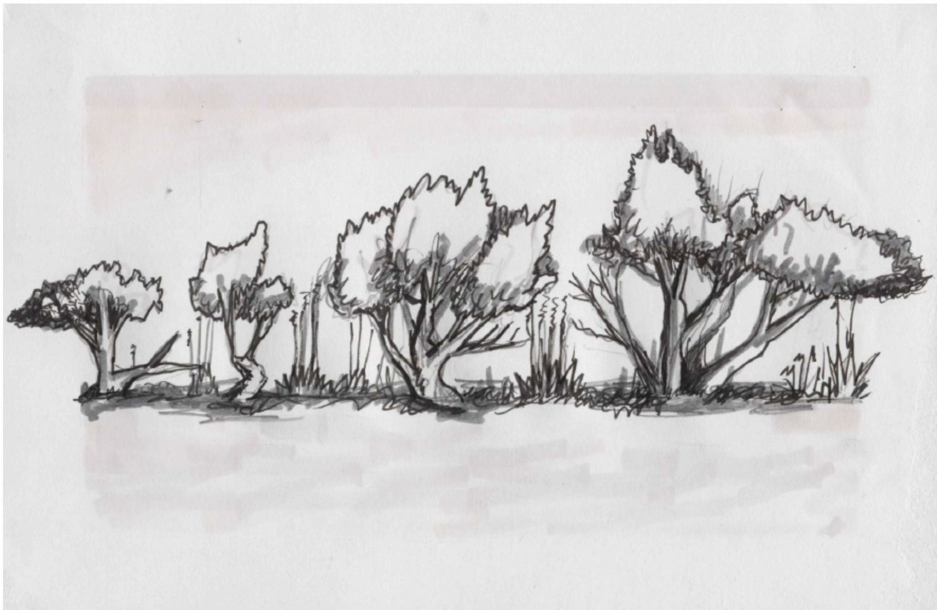

Figure 1.1. An illustration of a sagebrush steppe community, co-dominated by sagebrush and bunchgrasses, with understory forbs and annual grasses present

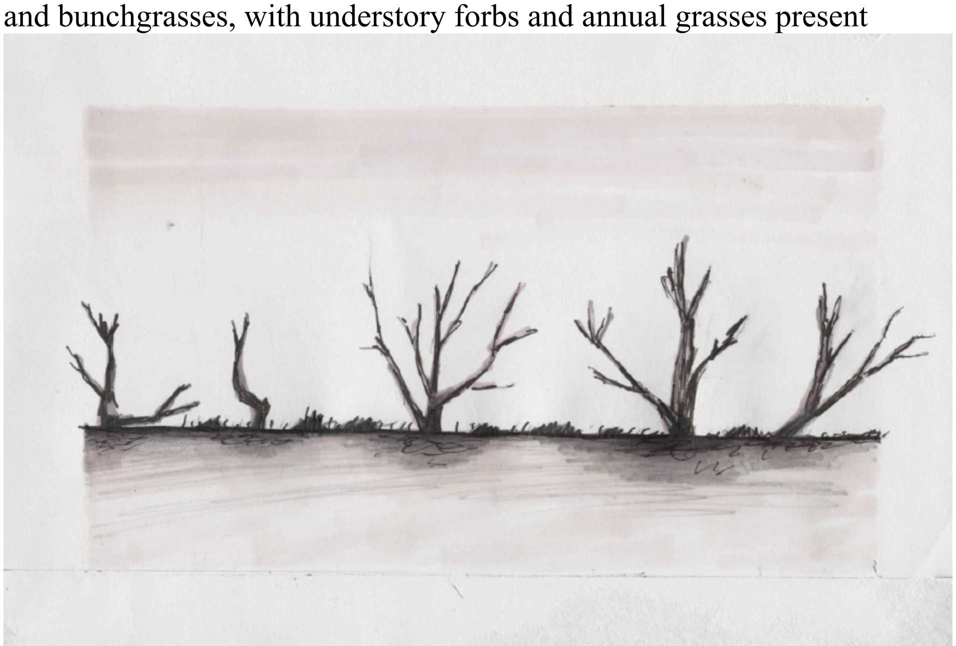

Figure 1.2. An illustration of a sagebrush steppe community immediately after a burn event. Nearly all aboveground biomass has been consumed, only skeletons of sagebrush remain. The intensity of the burn was greatest underneath the sagebrush, where large amounts of litter had accumulated and burned in a smoldering fashion.

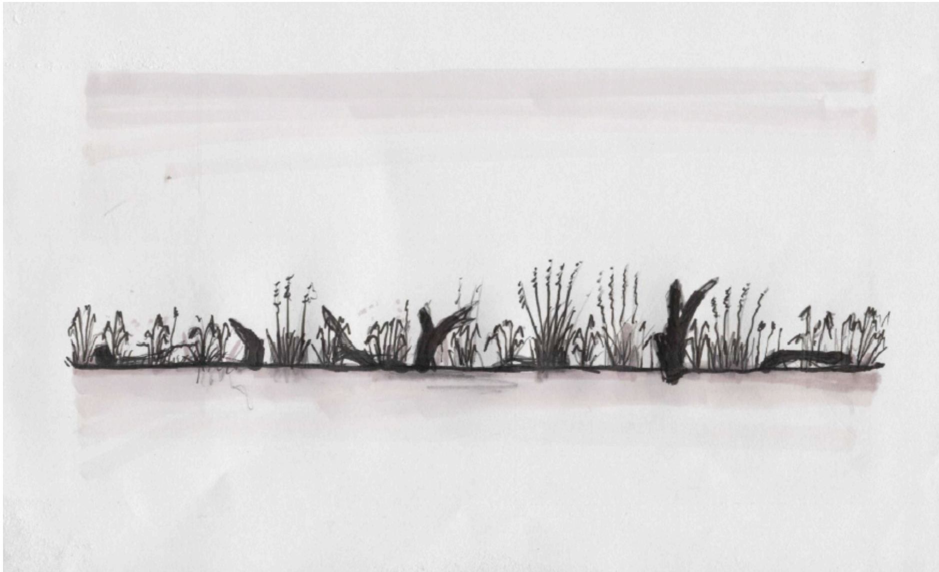

Figure 1.3. An illustration of a burn in the sagebrush steppe less than 10 years post fire. Bunchgrasses and perennial forbs have returned, but annual grasses are also co-dominant on the site.

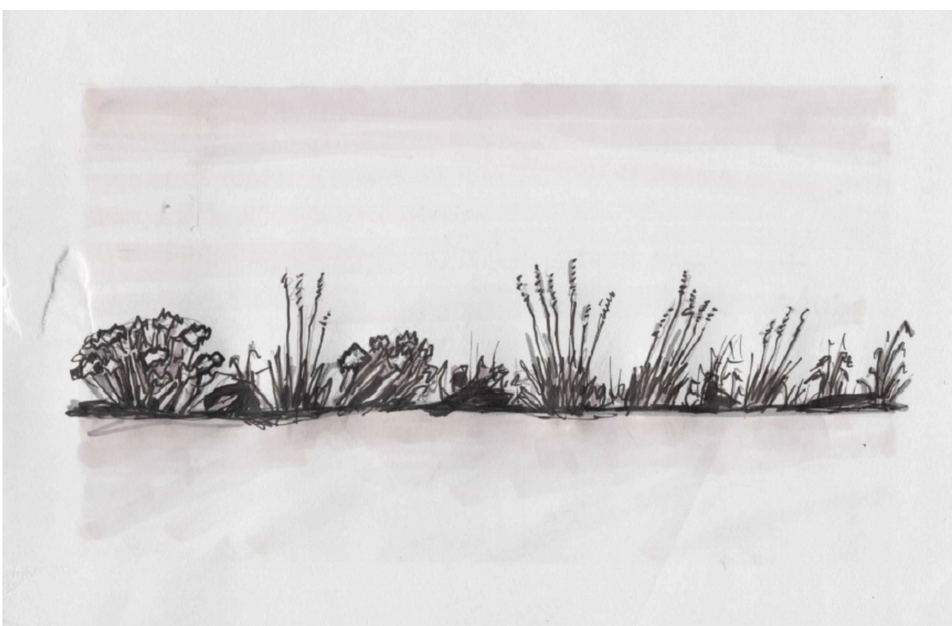

Figure 1.4. An illustration of a sagebrush steppe ecosystem where short statured re-sprouting shrubs like rabbitbrush and horsebrush have returned to the site post fire.

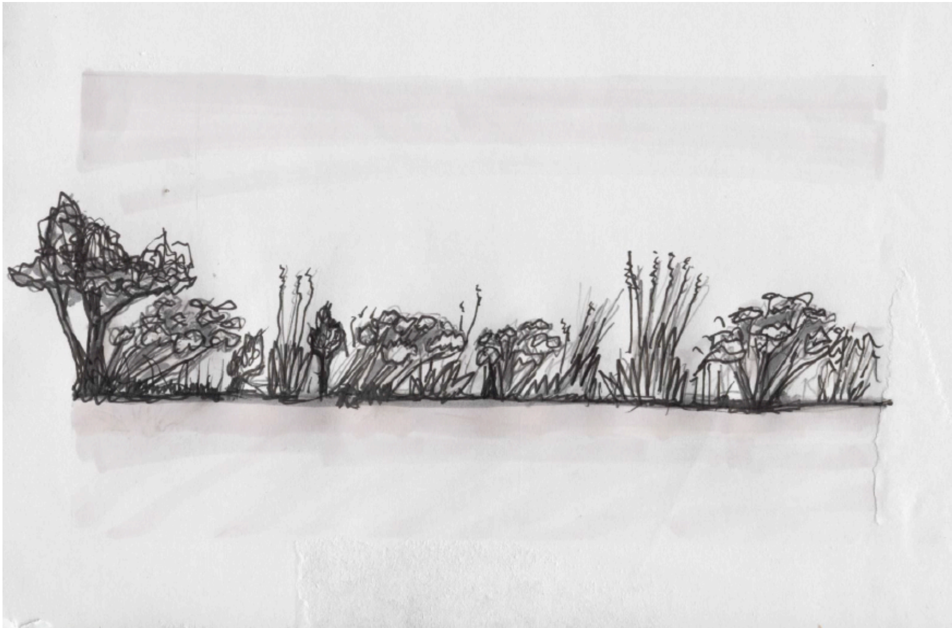

Figure 1.5. An Illustration of sagebrush retuning to a recently burned area from wind-driven seeds or seeds dormant in the seed-bank. As the sagebrush begin to mature they overtop shorter statured shrubs.

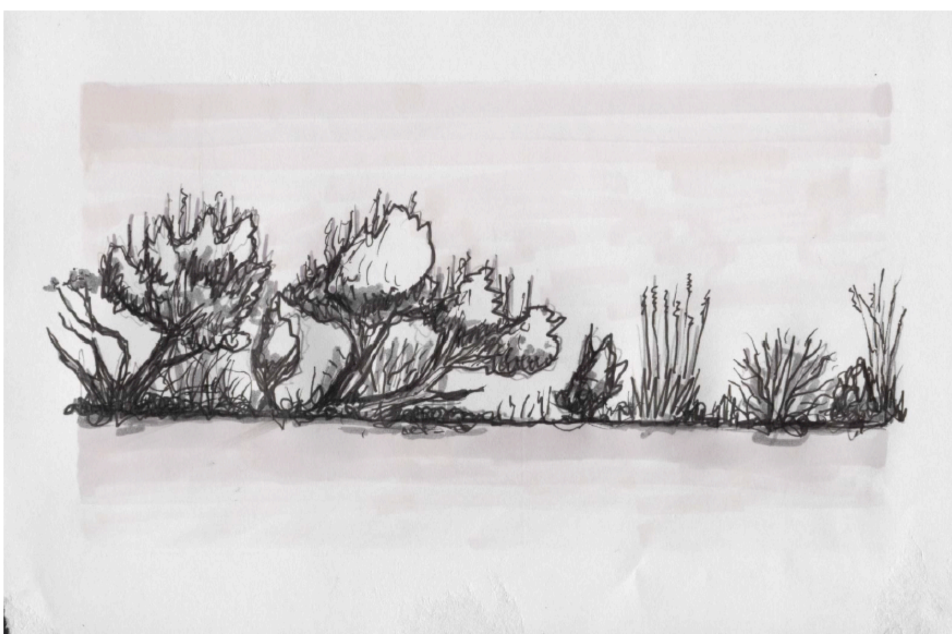

Figure 1.6. An illustration of sagebrush maturing and filling in the burned perimeter of a fire. This illustration could represent anywhere from <5 to >50 years post fire, depending on the sagebrush species, the nature of the burn, the proximity to the fire parameter, and the climate conditions post fire.

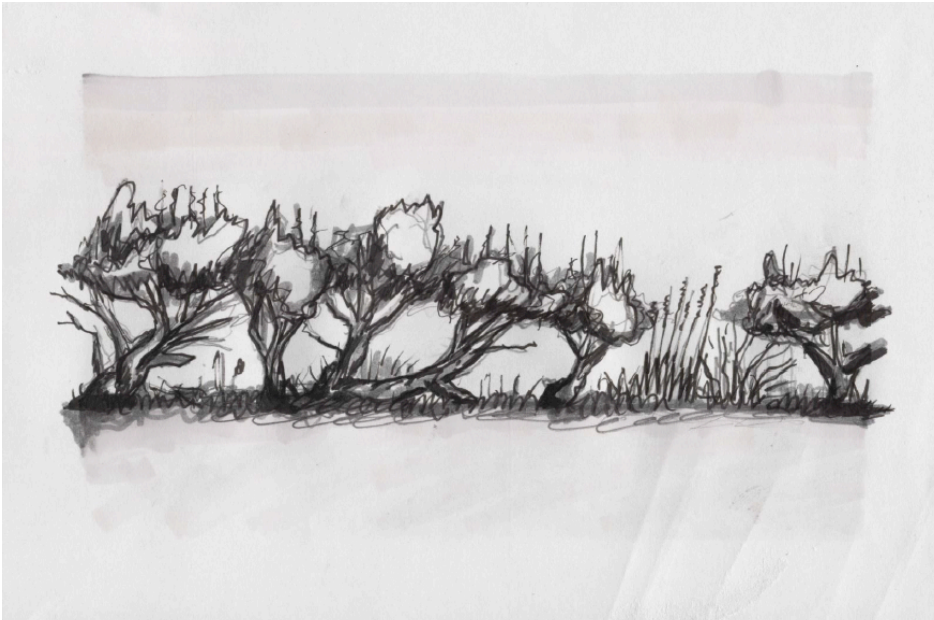

Figure 1.7. This illustration represents a mature stand of sagebrush steppe ecosystem. Sagebrush dominate the landscape, but bunchgrasses are still present, yet beginning to decline in dominance.

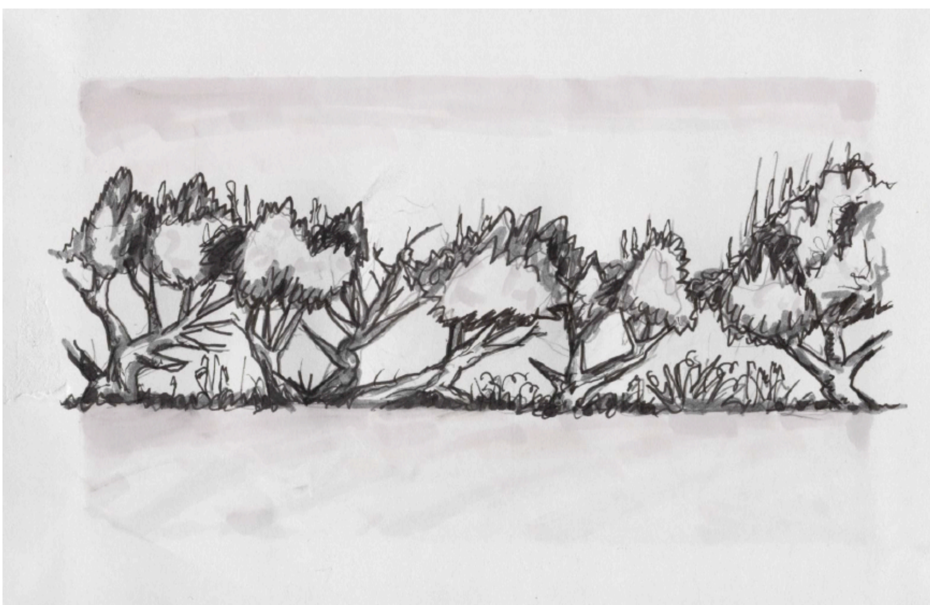

Figure 1.8. This illustration represents a stand of sagebrush in the sagebrush steppe that is perhaps outside of its historic range of variability for fire return interval, and may become at risk to lowered resilience post fire. The sagebrush have completely dominated the site. There is canopy closure and with a suppressed understory, few perennial bunchgrasses and a limited seed bank to replenish community with the forbs and grass after a fire.

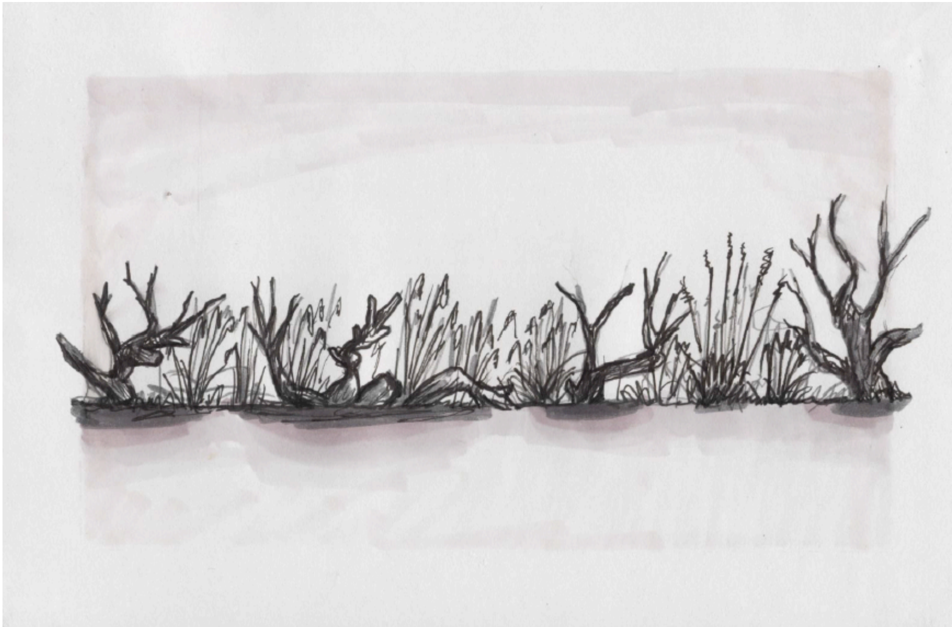

Figure 1.9. This illustration represents one year post fire in a sagebrush steppe community that burned with a suppressed understory, now dominated by invasive annual grasses, although some but few perennial bunch grasses have re-sprouted.

Figure 1.10. This is an illustration of a sagebrush steppe community that has transitioned into an alternative stable state dominated by annual grasses. Where the contiguous fuel bed provided by the annual grasses facilitates fire, and the frequent fires facilitate the dominance by annual grasses.

CHAPTER 2: FUEL SUCCESSION FOLLOWING FIRE IN WYOMING BIG SAGEBRUSH AT HART MOUNTAIN NATIONAL ANTELOPE REFUGE, OREGON

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ABSTRACT

Little is known about long-term patterns of fuel (biomass) following fire in Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) communities. This is one of the largest plant associations of the sagebrush steppe, where historically fire has been the primary disturbance factor. However, invasive species, historic overgrazing and anthropogenic factors such as land use change have altered fire regimes and therefore ecosystem structure and function. The rate and types of fuels that return following fire will impact future fire behavior, and affect site resistance and resilience, plant community succession, soil properties, and habitats for species of concern. To quantify fuels recovery following fire, we resampled fuels 17 years following prescribed fire in eight ~400ha plots (4 burned, 4 unburned control) at Hart Mountain National Antelope Refuge, OR, USA, where grazing by domestic livestock has not occurred since the early 1990s. This was a site first sampled in 1997. Total aboveground biomass had only recovered to 17% of pre-burn levels by 17 years post-fire. Grass and herbaceous fuels were five times greater in 17 year old burns than in unburned controls (no fire on record; P<0. 01). Downed woody debris was 7.5 times greater in unburned sites than in 17 year old burn plots (P<0.01), Shrub biomass was nearly 10 times greater in unburned plots than in burns (P<0.01), and litter mass under shrubs was 3.75 times greater in control than in 17 year old burn plots (P<0.01). Seventeen years after fire total shrub cover had recovered to 13.8% of that of unburned controls, and cover of sagebrush was 11.4% of the unburned controls. Results from this study show how composition, structure, and mass of fuels vary between mid-successional and late successional Wyoming big sagebrush sites

Keywords

Artemisia tridentata ssp. *wyomingensis,* fuel loads, Hart Mountain, long-term fire effects, prescribed burning, sagebrush steppe.

INTRODUCTION

Sagebrush steppe ecosystems are widespread across the western United States, and interacting factors including land use change, urban development, overgrazing, invasive species, and altered fire regimes currently threaten their sustainability (Crawford et al., 2004; Miller, 2011; Miller and Eddleman, 2001; Shultz, 2012). As a result, sagebrush-dominated ecosystems currently occupy approximately 60% (214,000 km^2) of their historic range (360,000 km^2), and have largely been replaced by invasive-dominated grasslands (Miller, 2011) and other land uses. Big sagebrush (*Artemisia tridentata*) is the most widespread species of sagebrush (Shultz, 2012) and the Wyoming big sagebrush subspecies (*A. tridentata* ssp. *wyomingensis*) covers the largest area of the big sagebrush subspecies (Miller and Eddleman, 2001; Tisdale, 1994). *A. tridentata* ssp. *wyomingensis* occurs at 150m-1,200m elevation (Miller and Eddleman, 2001), where annual precipitation is 18- 30cm (Miller and Eddleman, 2001; Shultz, 2009), and on soils that contain argillic, caliche, or silica layers (Miller et al., 2011). Compared to other big sagebrush subspecies, this range is generally lower in elevation, lower in precipitation, and at a higher temperature range (Mahalovic and McAurthur, 2004; Miller and Eddleman, 2001; Shultz, 2009; Tisdale 1994). Because of this, Wyoming big sagebrush communities have lower inherent resiliency (Chambers et al., 2014), a slower rate of succession following fire (Baker, 2011), and longer reported historic fire return intervals (50-100 years or more) than the more mesic sagebrush communities (Baker, 2006; Baker, 2011; Baker, 2013; Miller, 2011; Miller and Heyerdahl, 2008; Miller and Eddleman, 2011; Miller and Rose, 1999; Wright and Baily, 1982). Sagebrush ecosystems did not evolve under heavy grazing pressure (Mack and Thompson, 1982), but West (1999) estimates that greater than 99% of the sagebrush steppe has now been directly impacted by domestic livestock. Cattle grazing can impact fire regimes in the sagebrush steppe directly by altering herbaceous grass fuels and disrupting fuel continuity (Davies et al., 2010), and indirectly by altering plant community composition through preferential grazing, the release of woody species, and through trampling and the spread and facilitation of invasion of exotic annual species (Miller et al., 1994).

Exotic annual grasses are particularly disruptive to fire regimes of Wyoming big sagebrush communities, as they impact frequency, intensity, extent, type, and seasonality of fire (Brooks et al., 2004). The fine fuels contributed by cheatgrass (*Bromus tectorum*) and other annual grasses such as Medusahead rye (*Taeniatherum caput-medusae*) promote fire by increasing horizontal fuel continuity and creating a fuel-packing ratio that facilitates ignition and fire spread (Brooks et al., 2004; Davies and Svejcar, 2008). This alteration of fuels often results in a positive feedback loop in which fire facilitates invasion and invasion facilitates fire (Brooks et al., 2004; Chambers, 2014). The resultant altered fire regime often contains more continuous fires of larger total area that can decrease soil stability, and lead to loss of topsoil and available nutrients due to post-fire wind and water erosion (Hasselquist et al., 2011; Sankey et al., 2009). This cycle of fire and invasion can lead to the ecosystem transitioning into an alternative stable state where annual grasses dominate and fire can occur as frequently as <10 years between fire events (Miller, 2013; Miller and Eddleman, 2001; Westoby et al., 1989; Whisenant, 1990), far lower than the reported historic fire return interval of 50-100 years or more (Wright and Baily, 1982; Baker, 2006; Mensing, 2006).

To develop a better understanding of how the changes in fuel composition and structure occur over time in relatively intact, mid and late successional Wyoming big sagebrush communities, I quantified fuels accumulation in prescribed burns and adjacent, unburned control plots 17 years after ignition. I hypothesized that: *1)* total fuel loads would be greater in unburned plots than in those burned 17 years prior; *2)* shrub and woody fuels would dominate vegetation structure in the control plots, and herbaceous fuels would dominate in burn plots; and *3)* non-herbaceous litter and other burnable material that accumulated underneath shrub crown area would be one of the largest fuel components in both control and burned plots.

MATERIALS AND METHODS

Study Area

This study was conducted at Hart Mountain National Antelope Refuge (HMNAR), located 105 km northeast of Lakeview, OR, in Lake County (42°25’N’ 119°40’W). Elevation at the refuge ranges from 1,340m at its base in Warner Valley to 2,460m at the apex of Warner Peak (USFWS1994), but most of the refuge is 1800-2000m in elevation. Annual precipitation falls mostly as snow and varies based on elevation, from 15-20 cm along the western escarpment to 30-45 cm on the mountain. It is estimated that on average the majority of HMNAR receives fewer than 50 frost-free days per year (USFWS 1994). HMNAR encompasses approximately 120,000 ha in area with about 11,000 ha of its interior consisting of state, private, or county inholdings. HMNAR was founded in 1936 as a range and breeding ground for pronghorn antelope (*Antilocapra* *americana*; USFWS, 1994). Summer grazing by domestic sheep, cattle and horses occurred at the Refuge until 1946, when fenced pastures were established and grazing on the Refuge was limited to cattle and a few bands of feral horses. Stocking rates on the refuge from 1940-1989 averaged approximately 12,550 AUMs annually (Beschta et al., 2014). The process of removing all cattle from the refuge began in 1991 and by 1994 the practice of grazing by cattle had ended. Approximately 200-300 feral horses remained on the refuge until their removal in 1999, however from 2005-2012 approximately 250 feral horses trespassed on the refuge (Ellsworth et al., 2016).

Experimental Design

Eight adjacent plots were randomly assigned to either prescribed fire or unburned control (no fire on record, ≥50 years) treatments (N=4 for each treatment). All plots were located in the northeastern portion of HMNAR (Figure 2.1), with elevations ranging from 1,550m to 1,615m, with flat topography. Each burn unit was approximately 400 ha in area. Soils at all eight plots were cobbly clay-loam of the Ratto-Coglin series. Prior to treatment, vegetation was late succession Wyoming big sagebrush co-dominated by bottlebrush squirreltail (*Elymus elymoides*) and Sandberg's bluegrass (*Poa sandbergii*) (Wrobleski, 1999). Less than 2% cheatgrass (*Bromus tectorum)* cover was measured prior to treatment (Wrobleski and Kauffman, 2003). However, the high levels of bottlebrush squirreltail (10% cover of bunchgrasses, with 45% of all bunchgrasses being bottlebrush squirreltail; Wrobleski, 1999) may be indicative of a legacy of high levels of grazing (Reisner et al., 2013)

Ignition

Prescribed burn plots were ignited by heli-torch using a ring-fire ignition pattern between 23-27 September, 1997. On average 47% of the area within the plots was burned. Within the burned areas, all sagebrush biomass and approximately 80% of the understory biomass was consumed (Wrobleski, 1999). Understory fuel moisture for dead herbaceous vegetation ranged from 4.4-6.5% and moisture of 10-hour dead fuels was 5.5-8.0%. Flame length was 2.0-4.4m, rate of spread ranged from 4.6-12.0 m/min, and residence time was 0.6-2.6 minutes. Wind speed during the burns ranged from 6.4-9.7 km ha^{-1} (Wrobleski, 1999).

Field Measurements

Fuels were measured on burned and unburned sites in June and July of 2014 in order to determine total fuels accumulation 17 years following fire. Fuels were first divided into overstory (all living shrubs and dead shrubs still attached to the ground surface) and understory. Understory fuels were subdivided and quantified in the following categories: live herbaceous plant material (live), standing dead herbaceous plant material (standing dead), detached graminoid and herbaceous plant material (grass litter), shrub litter detached shrub leaves, organic duff and bryophytic materials (shrub litter), and downed woody debris (DWD). Within each plot, ten 20 m permanent transects (subplots) were established in 1997, and were relocated in this study. All transects located in the burn plots were established in areas where biomass was completely consumed by the fires.

Prior to ignition in September, 1997, overstory fuels were collected in the burn plots, and all methods were replicated in 2014. The line intercept method was used to determine shrub cover in each plot (Canfield, 1941). Length and height of all living and dead shrubs that crossed transects were recorded by species. Canopy gaps less than 20cm were included in measurements. Over-story shrub biomass was calculated using the Wyoming big sagebrush specific equation from Champlin 1983:

Total overstory biomass (kg ha^{-1}) =-2419.043+93.548(L) +62.537(H)

where (L)= the line intercept canopy cover in cm of Wyoming big sagebrush and (H) = the height in cm. Dead shrubs were multiplied by 0.25 to determine biomass as described by Champlin (1983). Cover of shrubs was determined by averaging cover across transects to give a plot level estimate.

Prior to ignition and 1YPF understory fuels were measured by clipping to bare mineral soil 25-20x50 cm quadrats randomly located in each plot, but were not further divided into fuels subclasses. In 2014, along each transect (n=10 per plot, n= 40 per treatment) three 20x50cm (0.1m^2) quadrats were established at meter marker 6, 12 and 18. Vegetation in each quadrat was clipped to mineral soil, and all burnable material was sorted in the field into the following fuels categories: live, grass litter, shrub litter, DWD. These samples were transported to Oregon State University and dried in ovens at 70° C for 48hrs and weighed to a .01g level of precision. Volume of DWD was determined using the planar intersect method described in Brown (1974).

Data Analysis

Analysis of variance (ANOVA) was used to test the differences in mean shrub cover and fuel loads by category (shrub, live herbaceous, dead herbaceous, grass litter, shrub litter) between treatments (burned or control). To test proportional or relativized fuel-loads by category, fuels by category per plot were also relativized by fuel type category at the subplot level. Relativization at this level has been show to have utility in examining shifts in composition of species or other ecological variables of concern (McCune and Grace, 2002), in this case fuel type categories. Differences in means were considered significant if *P* values were <0.05. Means are reported with standard errors (mean±se). RStudio, version 0.98.1091 was used for all analyses.

RESULTS

Fuel succession

Prior to fires, overstory biomass was 3444 kg ha^{-1} and understory biomass (DWD, herbaceous fuels, and litter) was 1545 kg ha^{-1} (Wrobleski, 1999). Cover of sagebrush averaged 22% across all plots before treatments (Ellsworth et al., 2016). Forty-seven percent of the area within the treatment plots was burned. Within completely burned patches (*i.e.* excluding unburned islands), all overstory biomass and 80±8% of the understory fuels were consumed, leaving 309 ha^{-1} in understory residual fuels (Wrobleski, 1999). Seventeen years after fires, overstory fuels had recovered to 438 kg ha^{-1} and understory fuels were 390 kg ha^{-1}. In unburned control plots, total fuels exceeded pre-burn levels, with overstory fuels totaling 4352 kg ha^{-1} and understory fuels accumulating to 1662 kg ha^{-1} (Figure 2.2). Total fuel loads were over 7x greater in controls (6015 kg ha^{-1}) than in burned plots (831kg ha^{-1}; $P<0.01$). Shrub biomass was ten times greater in control plots (4353 kg ha^{-1}) than burns (438 kg ha^{-1}; $P<.01$). Downed wood (DWD) biomass was 7.5 times higher in controls (1428 kg ha^{-1}) than in burns (191 kg ha^{-1}; $P<.01$). Shrub litter was nearly 4 times greater in controls (203.7± 23.5 kg ha^{-1}) than in burns (54.0±17.7 kg ha^{-1}; $P<.01$). Total understory fuels (DWD, shrub litter, grass litter, standing dead, and live) were over four times greater in controls (1662 kg ha^{-1}) than burn plots (390 kg ha^{-1}; *P*<0.01). Grass litter was an order of magnitude greater in burn plots (89 ha^{-1}) than in control plots (9 kg ha^{-1}; *P*<0.01). Standing dead biomass was three times greater in burned plots (45 kg ha^{-1} than in controls (15 kg ha^{-1}). Live grass and herbaceous fuels in burns (20 kg ha^{-1}) were more than double that of controls (6 kg ha^{-1}; *P*<0.01), and total herbaceous fuels (live + standing dead + litter) were 5 times greater in the burned plots (154 kg ha^{-1}) compared to controls (30 kg ha^{-1}; *P*<0.01). Total shrub cover (control= 29%, Burn=3%; *P*=0.01), and cover of Wyoming big sagebrush (control=21%, Burn=2%; *P*<0.01) were greater in the control plots (Table 2.1).

Relative fuel composition

When fuels were relativized by the total at the subplot level, there was a dominance of herbaceous fuels in burned plots (51%), and a dominance of woody fuels (88%; shrubs and DWD) in unburned controls. Shrub litter made up 10-12% of fuel loads, and did not differ across treatments (*P*=0.67; Table 2.2). Shrubs comprised were 60.5% of total biomass in control plots and 22.1% in seventeen-year-old burns (*P*<0.01). DWD comprised nearly twice as much of the fuel load (27%) in controls than in burns (14%; *P*=0.02). In contrast, herbaceous fuels were over 30 times greater in burns (51%) than controls (1.6%; *P*<0.01). Proportional grass litter was over 50 times greater in the burns (29%) than controls (0.5%; P<0.01). Standing dead herb and grass fuels were over 17 times greater in burns (15%) compared to controls (0.9%; *P*<0.01), and live herbs and grasses as a percentage of the total were 32 times greater in burns (6.4%) compared to the controls (0.2%; *P*=0.01; Table 2.2).

DISCUSSION

Seventeen years after fire at this site, cheatgrass cover ranged from 0.2-8.4% with no differences between treatments (Ellsworth et al., 2016). Across many Wyoming big sagebrush communities, however, post-fire shifts to dominance by invasive grass have been documented (Brooks et al., 2004; Miller et al., 2013). Reed-Dustin (2015) in a long-term study of Wyoming big sagebrush communities at the John Day Fossil Beds, Sheep Rock Unit, OR, found that sagebrush cover was not recovering 15 YPF. The sites from the Reed-Dustin (2015) study initially had cover of Wyoming big sagebrush of 14.12% and only recovered to 0.8% after 15 YPF. Pre-fire (49%) and 15YPF postfire (69%) cheatgrass levels were also very different than those observed at HMNAR (pre-fire>2%, postfire=0.2-8.4%; Ellsworth et al., 2016; Wrobleski and Kauffman, 2003). This emphasizes that post fire recovery Wyoming big sagebrush is highly variable by site (Wambolt et al. 2001).

Davis and Svejcar (2008) found that Wyoming big sagebrush communities invaded by medusahead did not have different total herbaceous fuel loads than adjacent un-invaded sites, although higher levels of detached litter and fuel continuity in invaded sites were observed, and likely exhibit different fire behavior than the un-invaded sites. The relatively high post-fire resilience in the sites from this study is likely due in part to a lack of post fire grazing pressure, few invasive grasses pre-fire, and burn treatments that resulted in high perimeter to area ratios, with unburned islands to act as native seed sources (Ellsworth et al., 2016; Reisner et al., 2013; Wrobleski, 1999).

Fire history, aspect, grazing regime, size and intensity of fire, and climate conditions favorable to sagebrush seed production, seedling establishment, and survival all may play roles in the recovery and succession of plant communities and fuels post fire (Maier et al., 2001; Zeigenhagen and Miller, 2009). Diamond (2009) examined highly degraded, cheatgrass dominated Wyoming big sagebrush sites in northwest Nevada, and found them to have fuel loads of 1,503kg ha^{-1} with 60% of the fuels being made up by cheatgrass. These sites had a mean fire return interval of 9.25 years over the past 5 fires, and is likely an example of an area that has shifted to a state of frequent fires and annual grass dominance. Even when cheatgrass is a dominant component of the fuel load post fire, in the absence of repeated fires it may lose dominance with time as perennial plants recover (Mata-Gonzales et al., 2007; Morris and Leger, 2016)

Consistent with my first hypothesis, total fuel loads 17 years after fire remained higher in unburned controls by almost an order of magnitude than in burn plots, primarily because woody fuels were much greater in control than in the burned plots. This is consistent with the slow rates of shrub recovery observed in these ecosystems, even in sites in good ecological condition (Ellsworth et al., 2016).

Consistent with my second hypothesis, herbaceous fuels still dominated the fuel composition of the burned plots and remained far higher than the unburned controls. (Table 2.2). Woody fuels (shrubs and DWD) were neatly ten times more abundant in the control plots compared to the burned plots, but shrubs were recovering 17 YPF, which is not always the case in long-term fire studies in Wyoming big sagebrush communities (Reed-Dustin 2015).

Within burned plots, there was high variability in shrub recovery, as only 12 of the 40 burned subplots had any shrubs at all. The total biomass of burn treatment subplots with shrubs (1978.1±501.8 kg ha^{-1}) was nearly six times greater than that in the burn treatment subplots without any shrub biomass (339.6±53.8 kg ha^{-1}), P<0.01. This demonstrates the patchy nature of succession in burned sagebrush. Shrubs establish from seed sources from outside of the burned perimeter, or from unburned islands (Miller et al., 2013), or from within the intra-burn area when weather conditions are favorable (Ziegenhagen and Miller, 2009).

Shrub litter was an important component in both control and burn plots, accounting for 10.6 and 11.4 percent of total fuels respectively, and should explicitly be considered in sagebrush steppe fuels and fire management. Even though shrub-related litter made up over 10% of the total aboveground biomass in both treatments, it was not one of the largest fuel components in either treatment scenario. Shrub litter and other ground fuels are largely consumed via smoldering combustion, and cause prolonged heating, potentially altering soil properties, and can damage perennial bunchgrasses, and kill seeds dormant in the soil seedbank (Rein et al., 2008), thus modifying post fire succession.

Cover of sagebrush was believed to be lower prior to settlement by Euro-Americans than today (Miler et al., 1994). Naturally-ignited fires and burning by Native Americans across the sagebrush steppe created a matrix of different fuel loads and successional stages (McAdoo et al., 2013) that now appears to be lost at HMNAR (USFWS, 1994). Under the current conditions there is a homogenized vegetation structure at HMNAR (USFWS, 1994). Wyoming big sagebrush communities with cover >20% may be at risk to large wildfires (Brown, 1982), particularly during drought periods or during extreme wind conditions. Britton and Clark (1985) proposed that 20% sagebrush cover, approximately 300 kg ha^{-1} of herbaceous fuels, and 24 km/hr winds are needed for fire spread in sagebrush dominated ecosystems. However, as sagebrush cover increases, the amount of herbaceous fuels needed for fire spread will decrease, and as wind speed increases, and relative humidity decreases, sagebrush cover and herbaceous fuel loading required for a fire to spread is lowered. Herbaceous fuels at the control sites (30 kg ha^{-1} in 2014), were an order of magnitude below the 300 kg ha^{-1} threshold described by Britton and Clark (1985), drought and severe weather conditions, inter-year variability of herbaceous fuel loads - especially invasive annual grasses, and the possibility of continued increases in sagebrush cover all combine to warrant continued investigations of the risk of future large area wildfires.

The results from this study show a resilient Wyoming big sagebrush ecosystem recovering post fire without domestic livestock or a dominance of invasive grasses (Ellsworth et al., 2016). Although total sagebrush cover in the burned treatment plots 17 YPF was only 2.3%, those subplots (12/40) in the burned treatment that contained any sagebrush, averaged a cover of 7.1%, and I predict based on a sagebrush recovery formula from Watts and Wambolt (1996) that it is possible for sagebrush in the burn treatment plots will reach >10% by 30 years post fire.

If future climate scenarios lead to a warmer climate and drought-like conditions as predicted (Cook et al., 2015), the ranges of sagebrush communities may shift upwards in elevation with communities currently dominated by mountain big sagebrush shifting to dominance by Wyoming big sagebrush, and Wyoming big sagebrush communities shifting towards desert shrub communities (Chambers et al., 2014). These shifts are also predicted to be punctuated after years where large areas of the landscape burn (Creutzburg et al., 2015). Therefore, it is of particular importance to understand patterns of recovery and post-fire fuels accumulation, not only in Wyoming big sagebrush communities, but in adjacent sagebrush communities as well, and future post fire management actions like re-seeding should anticipate these predicted shifts.

Maintaining or increasing resilience in these threatened and important ecosystems at multiple spatial and temporal scales may include a consideration of the natural role of fire in good condition Wyoming big sagebrush ecosystems. This study shows that under these conditions, fire can promote good condition early and mid- successional ecosystems that are integral to wildlife species of concern (Ellsworth et al., 2016). Conversely, fires that occur too frequently, or occur under prefire conditions of high cheatgrass cover, can lead to shifts towards cheatgrass dominated alternative stable states (Reed-Dustin, 2015; Williams et al., 2016). Management actions that increase the heterogeneity and diversity of successional stages and fuel loads across the landscape should be considered, they may increase resistance to large fires by acting as a fuel break, and may increase site resilience in the long-term by helping to maintain areas of an intact forb and bunchgrass understories that may be lost if stands of sagebrush go too long in between fire events.

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TABLES AND FIGURES

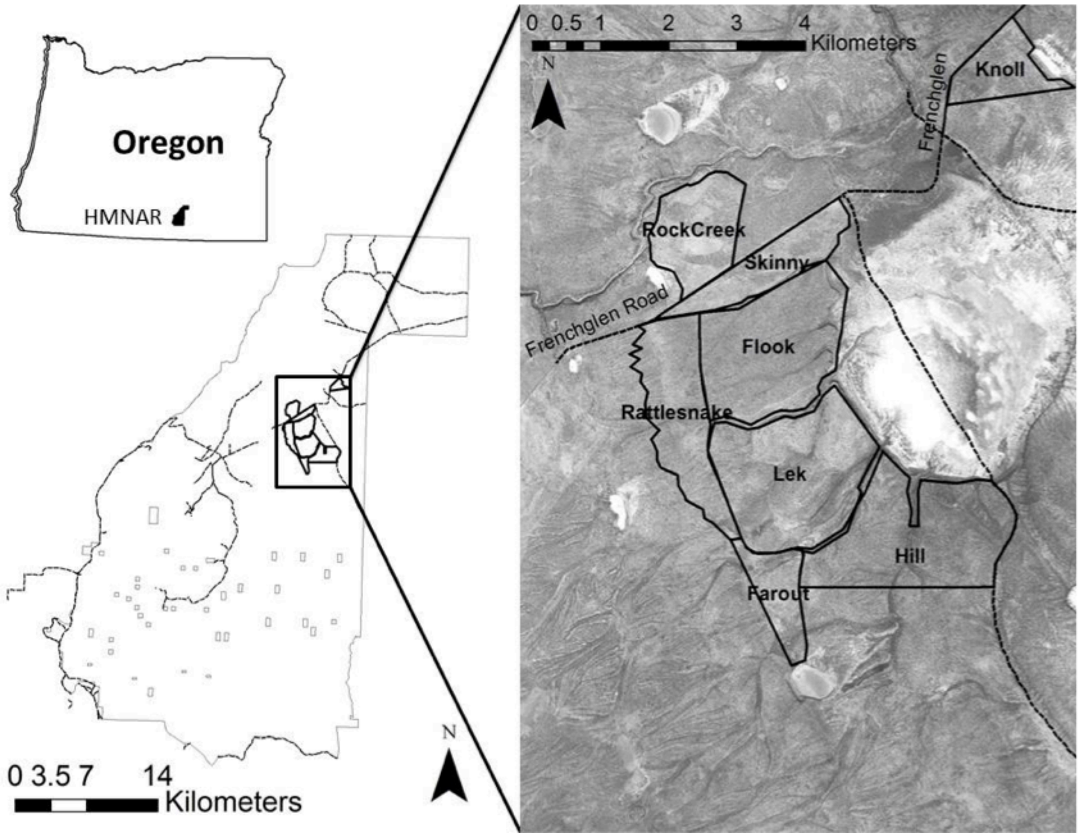

Figure 2.1. Map of site locations a Hart Mountain National Antelope Refuge, figure taken with permission from Ellsworth et al. (2016).

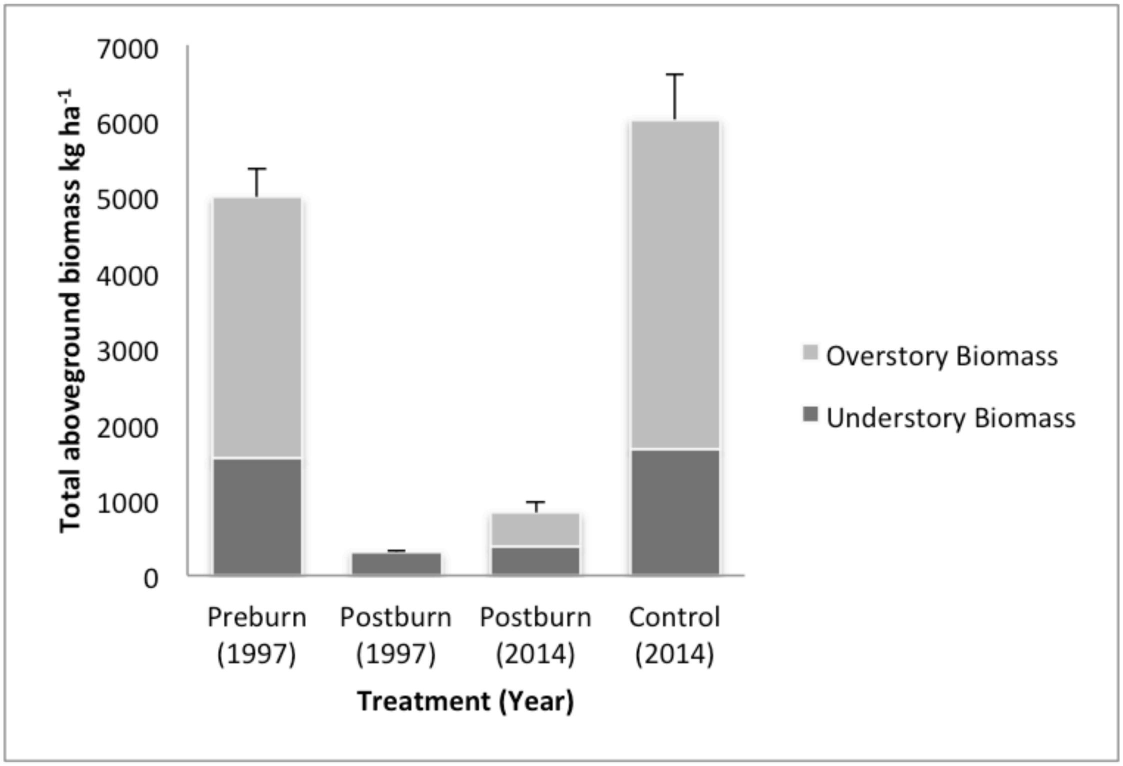

Figure 2.2. Total fuels (aboveground biomass; kg ha^{-1}) partitioned into overstory (light grey) and understory (dark grey) 17 years after prescribed fire at Hart Mountain National Antelope Refuge, Oregon, USA. The understory consists of DWD, grass litter, standing dead, live, and shrub litter. Pre-burn (1997), Post-burn (1997), Post-burn (2014), and Control (2014).

Table 2.1. Fuel accumulation (kg ha^{-1}) by fuels category for Wyoming big sagebrush communities at Hart Mountain National Antelope Refuge 17 years after prescribed fire and in adjacent unburned controls.

Fuels Category (kg ha^{-1})	**Control**	**Burn**	**F-value**	**P-value**
Downed woody debris	1428.48 ± 245.1	190.6 ± 66.8	23.744	<0.01
Shrub Litter	203.7±23.5	54.0±17.7	22.51	<0.01
Grass Litter	8.9±3.37	89.4±11.4	38.779	<0.01
Standing Dead	14.7±.54	45.1±8.7	25.851	<0.01
Live	6.35±1.56	19.97.0±3.95	10.28	<0.01
Herbaceous Fuels	30.23±4.51	154.4±19.9	53.468	<0.01
Total Understory	1662.4±243.96	389.7±66.7	24.966	<0.01
Shrubs	4352.48±646.24	438.3±148.9	34.92	<0.01
Total	6014.88±779.76	831.2±192.8	41.648	<0.01
Shrub Cover (%)	29.0±2.8%	2.9±1.1%	164.33	<0.01
ARTRW Cover (%)	21.0±2.0%	2.3±1.0%	66.75	<0.01

Table 2.2. Summary of fuels as a percentage of total fuels. Downed woody debris (DWD), litter accumulated under shrubs (Shrub Litter), detached grasses and herbs (Grass Litter), standing dead grasses and herbs (Standing Dead), live grasses and herbs (Live), Total Herbaceous Fuels (Grass Litter, Standing Dead, and Live); and shrub biomass as a percentage of unburned control for Wyoming big sagebrush communities at HMNAR initially burned September 1997, resampled Spring 2014.

Fuels Category	Control (% of total)	Burn (% of total)	F-value	P-value
DWD	27.2±3.7	14.3±4.1	5.45	0.02
Shrub Litter	10.6±3.1	12.4±2.9	.183	0.67
Grass Litter	0.5±.21	29.3±4.2	46.679	<0.01
Standing Dead	0.9±.26	15.4±2.2	41.134	<0.01
Live	0.2±.04	6.4±1.5	18.435	<0.01
Herbaceous Fuel	1.6±.045	51.1±5.9	70.119	<0.01
Total Understory	39.5±4.7	77.9±5.5	28.118	<0.01
Shrubs	60.5±4.7	22.1±5.5	28.118	<0.01

CHAPTER 3: POST-FIRE FUEL ACCUMULATION AND COMPOSITION IN BASIN BIG SAGEBRUSH ECOSYSTEMS OF THE SAGEBRUSH-STEPPE

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ABSTRACT

The sagebrush steppe is the largest semi-arid ecosystem in North America and faces many threats leading to loss of native species, degradation of wildlife habitat, altered fire regimes, and decreased resistance to invasion and resilience following disturbance. Basin big sagebrush (*Artemisia tridentata* ssp. *tridentata*) ecosystems, in particular, are greatly reduced in distribution and are not well-studied. Much of the land previously dominated by basin big sagebrush has been converted to other land use types, particularly agriculture, due to the frequent occurrence of these plant communities in fertile riparian floodplains. The natural fire regime in these ecosystems is not well defined. In particular, long-term fire effects in basin big sagebrush and the effects of repeated burns are poorly understood. In this study, I revisited and resampled two studies that were burned and measured in the late 1980's to gain a longer-term perspective of fuels accumulation following fire. Sites were on two different soil types, alluvial flood plain (Bear Creek) and pockets of deep fertile soil on north-facing slopes (John Day Fossil Beds National Monument [JODA]). The JODA site experienced a partial re-burn 10 years after the initial fire, providing an opportunity to quantify the effects of repeated burns on fuel structure and patterns of accumulation. At Bear Creek, there was high variability in rates of fuel recovery, ranging from 7-191% in 25 years (pre-fire, 16.8-36.2 Mg ha^{-1}; 25 years after fire, 2.3-69.1 Mg ha^{-1}). In contrast, in upland JODA sites fuel mass 26 years after fire (7.1-13.0 Mg ha^{-1}) consistently exceeded pre-fire fuel levels (6.2 Mg ha^{-1}). Repeated burns significantly altered fuels structure and composition. 15 years following a single fire (15YPF), herbaceous fuels made up 44% and shrubs were 39% of total fuels. Twice burned sites (2xB; burned 26 years and 15 years prior) had 71% herbaceous and 12% shrub fuel. Total fuel loads in 15YPF and 2xB sites ranged from 3.5-6.0 Mg ha^{-1} and did not differ by site (p=0.85). This suggests that repeated burns in close succession could alter rates and trajectories of fuel succession in basin big sagebrush communities.

Keywords

Artemisia tridentata spp. *tridentata*. Basin big sagebrush, fuel loads, long-term fire effects, repeated burns, sagebrush steppe.

INTRODUCTION

Basin big sagebrush (*Artemisia tridentata* spp. *tridentata*) historically occupied the most fertile and productive areas of the sagebrush steppe, but Euro-American settlers converted most areas once dominated by basin big sagebrush to agricultural land use types by the early 20th century (Shultz, 2012). For example, journals and historical photos by early explorers and settlers from Beaverhead County, Montana describe areas along broad stream terraces that had once been dominated by basin big sagebrush up to 2.5 meters in height are now converted to hay fields (Lesica and Cooper, 1997). In many areas basin big sagebrush is now relegated to pockets of fertile deep soil of mountain slopes and along roadways and fence-rows (Shultz, 2009) where annual precipitation is between 25-50 cm.

Historically, fire was the primary disturbance process in sagebrush-dominated ecosystems. Both naturally-ignited fires (Houston, 1973) and anthropogenic fires (McAdoo et al., 2013) played crucial roles in influencing plant community succession (Houston, 1973) and increasing the diversity and heterogeneity of the landscape mosaic (McAdoo et al., 2013). Much of our current body of research, however, focuses on the recovery period in the first few years following fire (Miller et al., 2013). Fire effects in the more common Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*) and mountain big sagebrush (*A. tridentata* ssp. *vaseyana*) ecosystems are better studied, but are complicated by a legacy of domestic livestock grazing, introduction of invasive species, and altered patterns of ignition (Brooks et al., 2004; Miller et al., 1994; Miller et al., 2013). It is estimated that fire historically occurred in xeric Wyoming big sagebrush communities every 50-100 years or more (Baker, 2006; Mensing et al., 2006; Wright and

Bailey, 1984), and in the mesic, more productive mountain big sagebrush as frequently as every 15-25 years (Burkhardt and Tisdale, 1976; Miller and Heyerdahl, 2008; Miller et al., 2001). The role of fire in basin big sagebrush ecosystems, however, is much more poorly understood, and the few existing studies provide insight to only a short time period following fire (Sapsis and Kauffman, 1991). Long-term perspectives of vegetation and structural change and fuels accumulations in basin big sage ecosystems are almost completely unknown (Miller et al., 2013).

To better understand how to manage remaining basin big sagebrush communities, as well as the habitat for wildlife species and the ecosystem services that they provide, it is important to understand the natural and current disturbance regimes, including the patterns of fuels accumulation following fire. Fuels are defined as the living and dead vegetation (biomass) that burns in a wildland fire (Pyne, 1984) including duff, grass, herbs, downed wood, shrubs, and trees (Byram, 1959). It has been proposed that due to relatively rapid primary productivity (Sapsis, 1990) and sagebrush canopy recovery (Lesica et al., 2007), basin big sagebrush may have historical fire return intervals that are intermediate (Sapsis, 1990) between mountain big sagebrush and Wyoming big sagebrush, or more frequent than both other subspecies (Lesica et al., 2007).

The objective of this study is to gain a better understanding of patterns of fuel structure and fuel accumulation, fire regimes, and potential future fire behavior in basin big sagebrush communities, and to gain a better understanding of how repeated burns affect fuel structure and successional trajectories. To achieve this objective, I quantified long-term post-fire fuels accumulation at two sites, Bear Creek and John Day Fossil Beds (JODA), both on the Columbia plateau in north-central Oregon. At both sites, previous research efforts have measured pre- and post-fire fuels, and at JODA, some plots reburned 11 years after the initial fire. I hypothesized that: *1)* due to the rapid recovery of basin big sagebrush, fuel loads and composition at sites >20 years post fire will be similar to pre-fire fuel loads and composition, with woody fuel (shrubs and DWD [downed woody debris]) composing the majority of the fuel biomass. *2)* Repeated fires will alter fuels accumulation and composition, such that sites that are twice burned (twenty-six years post fire [26 YPF] and fifteen years post fire [15 YPF]) will have less total fuel and less woody fuel compared to sites that only burned once (26 YPF or 15 YPF).

MATERIALS AND METHODS

Study Areas

This research was conducted at two sites where prescribed fire was set and fuels data were collected in the late 1980's in basin big sagebrush communities (Kauffman and Cummings, 1989; Sapsis, 1990). The Bear Creek plots are on an alluvial plain adjacent to Bear Creek on land managed by the Prineville District of the Bureau of Land Management (43°58' N, 120°41 'W) at 1100 meters in elevation. Plots were burned in spring (1989) and fall (1988) for a total of 6 plots. Each plot was approximately 0.18 hectares in area, with flat topography (Kauffman and Cummings, 1989).

The John Day Fossil Beds site is located within the Sheep Rock Unit approximately 12 km NW of Dayville, Oregon, USA (44°31'N, 119°38'W). Domestic livestock grazing has been excluded from the Monument since 1973. 12 plots of at least 0.15 hectares in area were burned in September 1987 (n=4) and May 1988 (n=5). Three (n=3) plots were established initially as controls. All plots were dominated by basin big sagebrush prior to burns, with Idaho fescue (*Festuca idahoensis*) and bluebunch wheatgrass (*Pseudoroegneria spicata*) dominating the understory. All plots have a north facing aspect with slopes ranging from 20-65% and elevations ranging from 700-869 meters. Soils are of the Simas-Tub association of very stony clay loam soils (Sapsis, 1990). Plots were previously sampled in 1987 and 1988 (pre-fire), in 1987 and 1988 (post-fire), and May-June 2015 (25YPF for fall burns, and 26 YPF for spring burns, all referred to from here on as 26 YPF). At JODA, a 1999 prescribed fire burned the sample area, re-burning five previously burned plots, and burning all plots which had previously been unburned controls. Plots that only burned once in 1987 or 1988 are referred to as 26 YPF (n=4), plots that only burned once in 1999 are referred to as 15 YPF (n=3), and plots that burned in both 1987 or 1988 and 1999 are called Twice Burned and referred to as 2xB in some figures.

Field sampling

Field methods followed those of original studies to ensure comparability across study years. At the Bear Creek site, I compared newly collected 25 YPF data with pre-fire (fall 1988, spring 1989) and immediate post fire (fall 1988, spring 1989) fuel loads and composition. At the JODA site I compared previously collected pre-fire (fall 1987, spring 1988) and immediate post fire (fall 1987, spring 1988) data with 26 YPF fuel load and composition data. At both sites fuels were partitioned into and quantified by category: live basin big sagebrush shrubs, other live shrubs, standing dead shrubs, downed woody debris (DWD), live herbaceous understory, standing dead herbaceous understory, grass litter, and shrub litter. Species, crown area and height of each shrub was measured along ten permanent 10x1 meter belt transects per plot at Bear Creek, and along five 15x1 meter permanent belt transects per plot at JODA. Shrub biomass was determined using previously developed allometric equations (Kauffman and Cummings, 1989: Champlin, 1983) using *in situ* crown area and height measurements. Downed wood was measured along each transect following methods described in Brown (1974).

Understory fuels were clipped to bare mineral soil in twelve 30x60cm subplots per plot at Bear Creek and ten 30x60cm subplots per plot at JODA. Clipped fuels were subdivided into the following categories: live herbaceous fuels, dead herbaceous fuels, and duff (detached non-woody shrub material, mosses and lichens, and the organic duff layer). Fuels were oven dried at 70° C for 48 hours and weighed. To determine cover of basin big sagebrush, shrub density was determined from basin big sagebrush counts along all permanent belt transects density per transect was then multiplied by the average crown area for basin big sage brush for each transect, and data was then averaged across transects and scaled to get a plot-level cover estimate.

Data Analysis

Analysis of variance (ANOVA) was used to test for differences between fuel loads for each fuel type (dependent variable) at each site. Time of measurement (pre-fire, post-fire, and 25 YPF at Bear Creek; 26 YPF, 15 YPF, 2xB at JODA) was the independent variable. Significance level was set at $\alpha<0.05$. Significant differences between groups were determined using Tukey-Kramer honest significant difference (HSD) post hoc analysis. To test the relative proportion of fuel loads, each category of fuel was relativized by the total fuel at the subplot level. Relativization at this level has been shown to be effective in examining shifts in composition of species or other ecological variables of concern (McCune and Grace, 2002), in this case fuel type categories. All analyses were performed with RStudio version 0.98.1091

RESULTS

Bear creek

Fires reduced total fuel loads by nearly 4 fold, (pre-fire=27.5 Mg ha^{-1}, post-fire 7.3 Mg ha^{-1}), twenty-five years post fire fuels had recovered to over 97% of pre-fire levels, however total fuels recovery was highly variable ranging from 2.3-69.1 Mg ha^{-1}. Rate of biomass accumulation, defined as total biomass divided by years since fire, was 1.08±0.37 Mg ha^{-1} per year.

Fires reduced shrub fuel loads from 10.8 to 3 Mg ha^{-1}, and 25 YPF shrub fuel loads (21.7 Mg ha^{-1}) were double that of pre-fire levels. Proportional shrub fuels were lower before (40%) and immediately after (39%) fire than at 25 YPF (71%). Pre-fire sagebrush canopy cover pre-fire (30%), was reduced to 5% by fire and by 25 YPF, sagebrush cover had reached more than double that of pre-fire levels at 77%. Sagebrush canopy cover at time of re-measurement was 233.4±61.8% of pre-burn levels, a rate of 9.36±2.47% increase each year. Density of sagebrush at 25 YPF was 7600±2017 sagebrush ha-1. Mean height of mature sagebrush at 25 YPF was 1.39±0.24m.

Before burns, DWD was 7.2 Mg ha^{-1}, was reduced post-fire to 1.8 Mg ha-1, and after 25 YPF recovered to 4.2 Mg ha^{-1}. Herbaceous fuels made up a very slight amount of total fuels for all time periods (1-3% of total fuels). Herbaceous fuels were reduced from 0.7 to 0.13 Mg ha^{-1} by fire, and after 25 years post-fire herbaceous fuels only measured 0.2 Mg ha^{-1}. Pre-fire duff fuel loads were 8.8 Mg ha^{-1} comprising 30% of fuels, and immediately post fire they declined to 2.4 Mg ha^{-1} comprising 32% of fuels. By 26YPF duff fuels had not recovered, measuring only 0.6 Mg ha^{-1} and making up 3% of total fuels (Table 3.1, Figures 3.1, 3.2)

John Day Fossil Beds, Sheep Rock Unit

The original study at JODA was to evaluate short term effects of spring and fall burns. Sapsis (1990) reported that pre-fire fuel loads were Fall=10.59±1.12 Mg ha^{-1}, Spring=6.32±0.69 Mg ha^{-1}. However, the prescribed fire in 1999 burned the entire area. The 26 YPF plots consisted of all spring burns so the pre-fire mean of 6.32±0.69 Mg ha^{-1} was used when computing recovery of biomass. The twice burned plots consisted of four fall burns and one spring burn so a mean of 9.7 Mg ha^{-1} (based on the average fuel loads of four fall burn plots and one spring burn plot) was used as the pre-fire fuel load when computing recovery of biomass. The fuel loads of the unburned control plots were not measured in 1987 or 1988. Prior to fires, the 26 YPF plots at JODA had total fuel loads of 6.23±0.69 Mg ha^{-1} and during the fire approximately 90% of fuels were consumed (Sapsis and Kauffman, 1991). When re-measured 26YPF, plots had total fuel loads of 9.3 Mg ha^{-1}, which was higher than fuels in any of the plots that burned 15 years prior (Table 3.2). In the 15 YPF sites, total fuel loads were 4.5 Mg ha^{-1}. At the twice-burned sites (2xB) prior to initial burning, total fuel loads were 9.71 Mg ha^{-1}, and when re-measured in 2014 they were 4.6 Mg ha^{-1}. Total fuel loads did not vary significantly between 15YPF and twice burned sites, though composition was different (Table 3.2, Figure 3.4).

Shrub mass differed between fire histories ($P<0.01$), with higher shrub fuels in 26YPF plots than either in 15YPF or 2xB plots. Shrub fuels at the 26 YPF plots in 2014 were 5.2 Mg ha^{-1} and comprised 56% of the total fuel loads. In the 15 YPF plots shrub fuel loads were 1.8 Mg ha^{-1}, comprising 39% of fuels, and in the twice-burned plots shrub fuel loads were 0.6 Mg ha^{-1} making up 12% of total fuels. Proportional shrub fuel loads in once burned sites (26 YPF and 15YPF were significantly higher than those in 2xB plots (Table 3.2). Prior to burning, sagebrush cover in the 26 YPF plots was 7.5% (Sapsis, 1990). In 2014 it was 18.24±1.85%. In the 15YPF and 2xB plots, sagebrush canopy cover was significantly lower, at 3.8% and 1.0%, respectively (Table 3.2).

In 2014, the mean density of sagebrush in 26 YPF sites was 3028±533 sagebrush ha^{-1}, significantly higher than that of either plot that burned 15 years ago (P <0.01, F=14.24). The mean density of sagebrush at 15YPF plots in 2014 was 1200±601 sagebrush ha^{-1}, and at 2xB plots in 2014 it was 160±106 sagebrush ha^{-1}. Height of mature sagebrush was not significantly different (P=0.25, F=1.58), at 0.76±0.14m across all fire histories.

Recovery of total fuels in terms of total fuels in 2014 divided by prefire fuel totals did vary between fire histories (P<0.01, F=23.79), with higher recovery at 26 YPF(148.5±20.62%) than in twice burned plots(49.40±6.88%). 15 YPF plots were excluded from analysis because measurements of pre-fire fuel loads did not exist. Rate of biomass accumulation (total biomass divided by years since fire) at JODA did not differ between fire histories (P=0.34, F=1.23), at 0.32±0.02 Mg ha^{-1} per year.
Herbaceous fuels were greater in twice burned plots (3.2 Mg ha^{-1}) than in either 15YPF (2.0 Mg ha^{-1}) and 26 YPF (1.4 Mg ha^{-1}). Proportional herbaceous fuels were also significantly greater in 2xB (71%) plots than in 26YPF plots (16%). Proportional herbaceous fuels in 15YPF plots (44%) was intermediate between 2xB and 26 YPF plots. Duff fuels were significantly greater in 26 YPF plots (2.3 Mg ha^{-1}) than in either twice

burned (0.5 Mg ha^{-1}) or 15 YPF plots (0.7 Mg ha^{-1}), however relativized duff fuels ranged from 10-25% and did not vary between fire histories (P=0.19; F=2.00)

DISCUSSION

Bear Creek

Not only had total fuels and shrub fuels recovered to pre-fire levels, and canopy cover was >200% of pre-fire levels 25 YPF, but in the interspace where mature sagebrush had not returned, seedlings were present, indicating ongoing regeneration and infilling. However, the site had not recovered precisely to pre-fire conditions. Perhaps the most surprising result from Bear Creek is the lack of duff layer formation following fire. The low mass of the duff layer at 25YPF may be due to post-fire wind erosion, which can be up to 67 times greater in recently burned areas than in unburned areas of the sagebrush steppe (Sankey et al. 2009), although it must be noted that the Sankey et al. (2009) study was conducted in a large fire (>80,000 ha) that was previously dominated by Wyoming big sagebrush. This lag in duff accumulation may indicate an unexpected fuels accumulation dynamic where immediately following fire herbaceous fuels dominate, followed by shrub dominance, and then an increase in duff and dead shrub material as sagebrush senesce and die, adding to the duff layer and detracting from shrub fuels. Prior to the initial burning the plots at Bear Creek had not likely burned for many decades. The rate of canopy cover recovery of 9.4% $year^{-1}$ at seen on this site is more than three times greater than that reported for basin big sagebrush at sites in southwest Montana (3.0 ± 1.3% year-1; Lesica et al., 2007).

John Day Fossil Beds, Sheep Rock Unit

With time since fire, shrub establishment, fuel loads, cover, and density increased, but structure and composition of fuels depended on fire history. Reed-Dustin (2015) measured the recovery of Wyoming big sagebrush at different plots that had burned 15 years prior at JODA in the Sheep Rock Unit, and found that sagebrush cover had recovered only to 0.8% cover from initial cover of 14.12%. This is similar to the 4% and 1% cover in the 15YPF and 2xB plots from this study. The difference, in part, between this study and this one may be that all of these burn plots were on more resilient north-facing slopes. Additionally, it is expected that recovery in Wyoming big sagebrush will be slower than basin big sage (Miller et al., 2013).

It is likely that successive repeated burns will compound a reduction in sagebrush reestablishment and result in longer periods of dominance by herbaceous fuels following fire. If Beardall and Sylvester (1976) are correct in their prediction that 0.67 Mg ha^{-1} of herbaceous fuels is needed for prescribed fires to spread in sagebrush ecosystems, then all three fire history treatments (26 YPF, 15 YPF, and 2xB) are at risk of reburning if ignition occurs. Repeated burns within this time frame may not be outside of the historic range of variability for basin big sagebrush communities of the Columbia Basin of the sagebrush steppe. As pointed out by Daubenmire (1942), the rapid agricultural development by Euro-Americans makes ecological comparisons to pre-settlement conditions difficult. The northern and western regions of the Columbia Plateau were frequently burned by Native Americans resulting in low levels of sagebrush cover and sustained dominance of bunchgrasses and herbaceous fuels (Daubenmire, 1942). Daubenmire (1942) clipped and measured all grasses and forbs from a plot within a graveyard near Lamont Washington. The graveyard was established in 1889 and it was protected from disturbance by domestic livestock, and not developed for agricultural purposes. He reported 1.14 Mg ha^{-1} of herbaceous fuels; similar to the 1.4 Mg ha^{-1} of herbaceous fuels in the 26 YPF plots at JODA, but lower than the approximately 2-3. Mg ha^{-1} in the 15YPF and 2xB plots. However, the sagebrush cover reported by Daubenmire (1942) of 2.2% is closer to that from the 15YPF and 2xB plots, 1-4%. Daubenmire (1942) hypothesized that the low levels of sagebrush cover and the bunchgrass dominance observed within the boundaries of the graveyard were the typical conditions of much of the Columbia Plateau prior to Euro-American settlement.

Sagebrush Recovery

One method used to measure post fire recovery of sagebrush dominated ecosystems (Lesica et al., 2007) is to divide total sagebrush cover by pre-fire sagebrush cover (or the sagebrush cover of an adjacent control plot), then divide that ratio by years since fire and express the results as a yearly rate of sagebrush recovery. One issue presented by this method is that sagebrush cover has been shown to recover in a non-linear fashion, along a sigmoidal pathway (Watts and Wambolt,1996). Lesica (2007) found recovery rates at basin big sagebrush sites in southwest Montana with a mean of 24 years post fire to be 3.0±1.3% per year; a rate intermediate from those seen at the JODA and Bear Creek sites in this study.

There was rapid recovery of basin big sagebrush at Bear Creek (25 YPF) and JODA (26 YPF) reaching over 200% of prefire sagebrush canopy cover and over 99% of prefire total biomass. The loss of duff layer at Bear Creek was unexpected, and differed from either pre-fire composition or that seen at JODA. At JODA repeated burns altered fuel succession leading to prolonged periods of herbaceous fuel dominance and lower shrub fuel loads and cover, though they remain native dominated, and do not appear to be at risk of transition to an alternative stable state of invasive grass dominance. It is likely that additional fires would prolong herbaceous dominance, which may result in fuel loads, composition, and community structure that resembles the conditions that existed in the Columbia Plateau prior to Euro-American settlement (Daubenmire 1942). This information will be helpful for public and private land managers, fire ecologists, and wildlife managers, working with sagebrush-dominated ecosystems. Rates of fuels accumulation and total aboveground biomass will be useful for those working with carbon stocks and landscape level changes under future climate scenarios.

Acknowledgements

This study would not be possible with out foresight of the scientists who first concocted these experiments. Thank you Dave and Arlene Sapsis. Thank you J. Boone Kauffman and Dian Cummings. Thank you to the co-authors for their support and input. Thank you to the field technicians that helped with data collection: Bobby Burdick, Lauren Christy Cimarron Kauffman, Emily Platt, and Neil Rosenquist. Thank you to the Prineville BLM, and the National Park Service for permitting me to collect data on your land. Thank you to Joint Fire Science for funding this project (project #14-1-02-5), and thank you to Lisa Ellsworth and J. Boone Kauffman for securing this funding.

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TABLES AND FIGURES

Table 3.1. Mean fuels plus standard error (Mg ha^{-1}) by fuel type category in *Artemisia tridentata* ssp. *tridentata* plots at Bear Creek in North Central Oregon. A "P" in front of the fuel type category represents proportional totals. Also shown is percent sagebrush cover (% SB cover). Pre-fire fuels were measured in the fall of 1988 or the Spring of 1989. Post-fire fuels were measured one day after burning. Fuels were then remeasured in the early summer of 2015 (25 YPF).

Bear Creek	**Pre-fire**	**Post-fire**	**25 YPF**		
Fuel type	**mean±se**	**mean±se**	**mean±se**	**f-value**	**p-value**
Shrubs	10.79±0.81(ab)	3.04±1.13(b)	21.72±7.68(a)	4.31	0.03
DWD	7.21±0.78(a)	1.76±0.62(b)	4.24±1.62(ab)	6.17	0.01
Duff	8.77±2.1(a)	2.38±0.87(b)	0.61±0.21(b)	10.61	0.01
Herb	0.72±0.17(a)	0.13±0.07(b)	0.23±0.09(b)	7.14	0.02
Total	27.48±3.14(a)	7.3±2.56(b)	26.8±9.23(a)	3.81	0.04
P.Shrub	40±2%(a)	39±4%(a)	71±12%(b)	6.28	0.01
P.DWD	27±2%(a)	27±4%(a)	24±11%(a)	0.93	0.06
P.Duff	30±4%(a)	32±4%(a)	3±0%(b)	25.56	<0.01
P.Herb	3±1%(a)	1±1%(a)	2±1%(a)	1.28	0.31
% SB cover	30±5%(a)	6±3%(a)	76±18%(b)	11.57	<0.01

Table 3.2. Mean fuels plus standard error (Mg ha^{-1}) by fuel type category in *Artemisia tridentata* ssp. *tridentata* plots at John Day Fossil Beds, Sheep Rock Unit in North Central Oregon. A "P" in front of the fuel type category represents proportional totals. Also shown is percent sagebrush cover (% SB cover). Results are shown for plots that burned once twenty-six years prior to measurement (26 YPF), once fifteen years prior to measurement (15 YPF) and twice, twenty-six years and 15 years prior to measurement (2xB). Results are from measurements taken in the summer of 2014.

JODA	**26 YPF**	**15 YPF**	**2xB**		
Fuel type	**mean±se**	**mean±se**	**mean±se**	**f-value**	**p-value**
Duff	2.29±0.8(a)	0.65±0.03(ab)	0.47±0.14(b)	5.56	0.04
Herb	1.4±0.19(a)	1.97±0.25(a)	3.16±0.16(b)	24.12	<0.01
DWD	0.37±0.13(a)	0.09±0.02(a)	0.39±0.22(a)	0.75	0.5
Shrubs	5.23±1.12(a)	1.78±0.32(b)	0.57±0.17(b)	13.88	<0.01
TOTAL	9.29±1.29(a)	4.48±0.49(b)	4.59±0.37(b)	11.21	<0.01
P.Duff	25±9%(a)	15±3%(a)	10±3%(a)	2	0.19
P.Herb	16±2%(a)	44±3%(ab)	71±7%(b)	25.7	<0.01
P.DWD	3±1%(a)	2±0%(a)	7±4%(a)	1.07	0.38
P.Shrubs	56±11%(a)	39±3%(a)	12±3%(b)	13.22	<0.01
% SB cover	18±2%(a)	4±2%(b)	1±0.6%(b)	46.02	<0.01

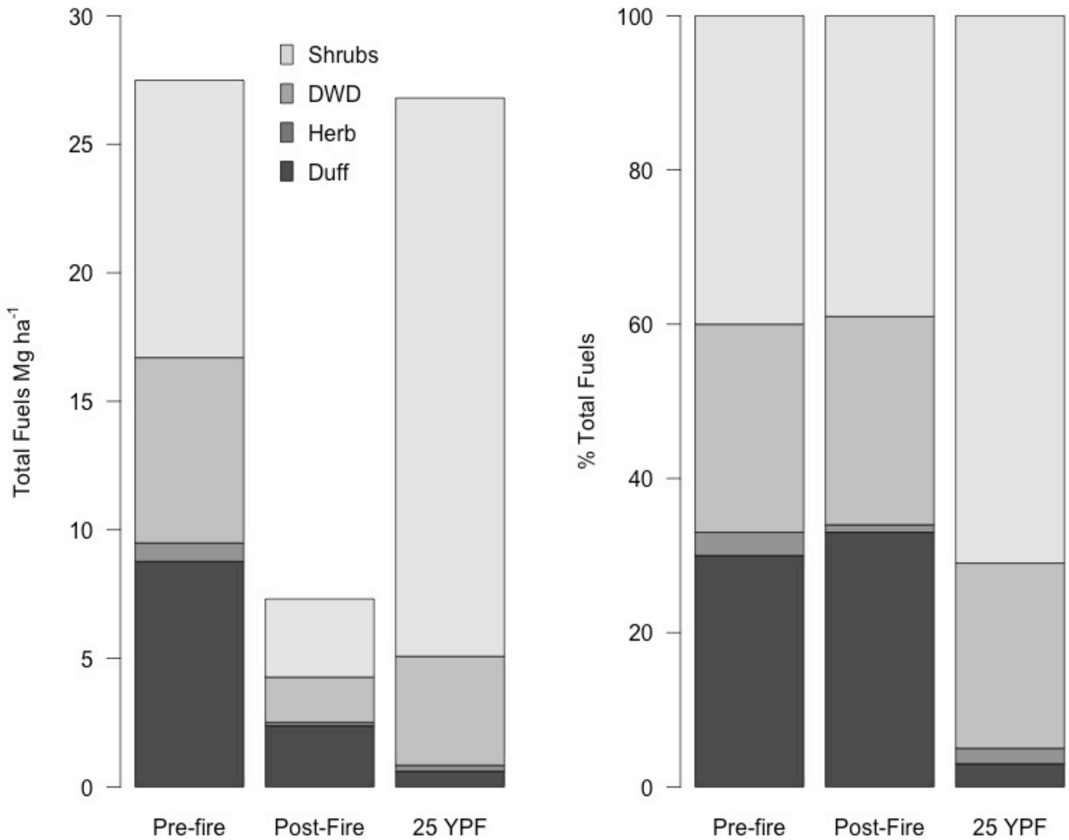

Figure 3.1. (Left) Mean fuel loads (Mg ha^{-1}) in *Artemisia tridentata* ssp. *tridentata* plots at Bear Creek (n=6) in North Central Oregon, prior to prescribed burns (Pre-fire) and immediately following fire (Post-Fire), and twenty five years post fire (25 YPF). (Right) Proportional fuel loads (Shrub, downed woody debris, herbaceous (live and dead grass and forbs) and duff (including detached shrub leaves and bryophytic material), at Bear Creek in North Central Oregon pre-fire, immediately post-fire, and twenty five years post fire.

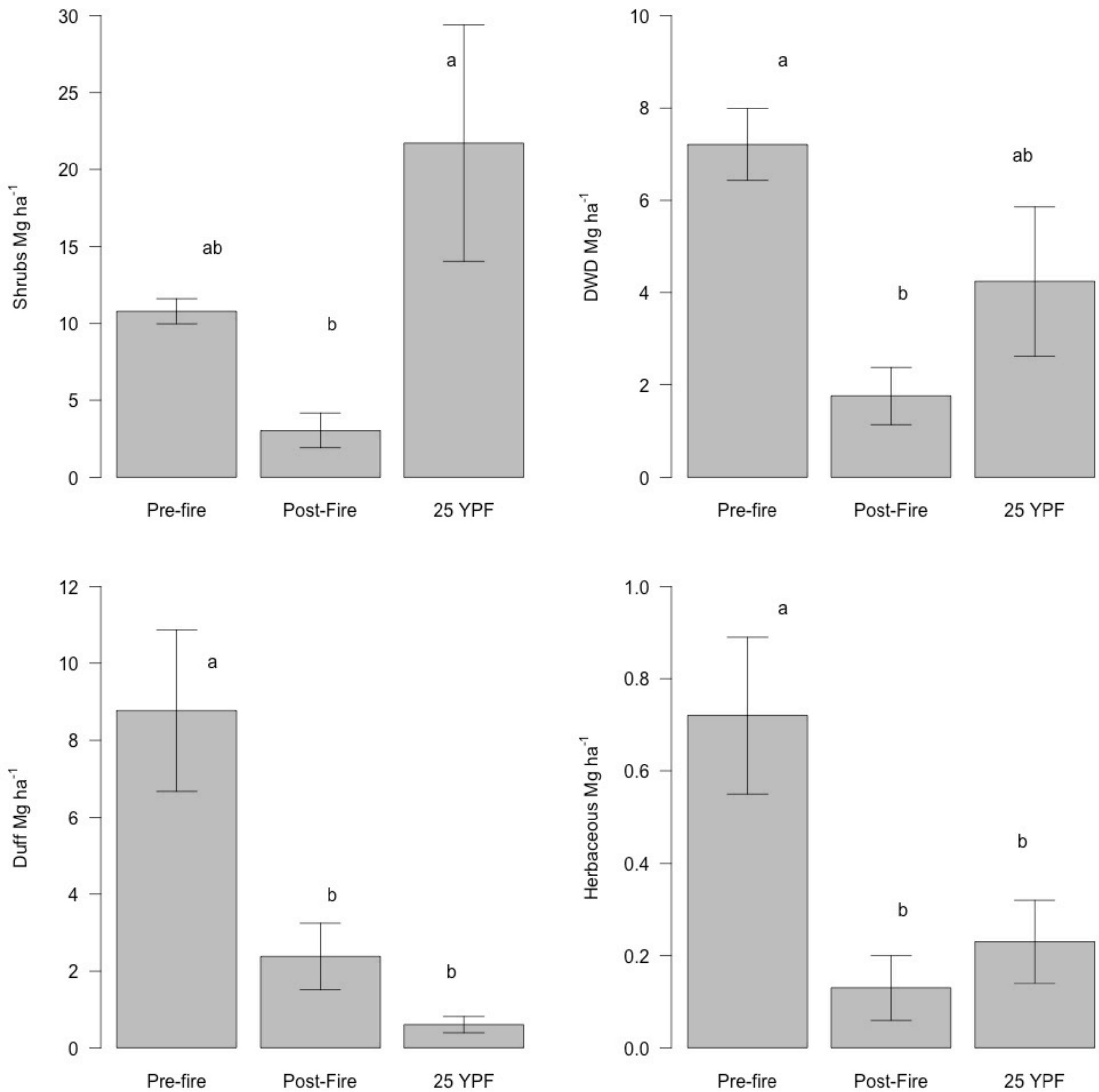

Figure 3.2. Fuel loads by fuel category in *Artemisia tridentata* ssp. *tridentata* plots at Bear Creek, North-Central Oregon pre-fire, immediately post-fire, and 25 years following fires (25 YPF). Error bar shows one standard error. Same letters over bars signifies no significant difference in fuels loads.

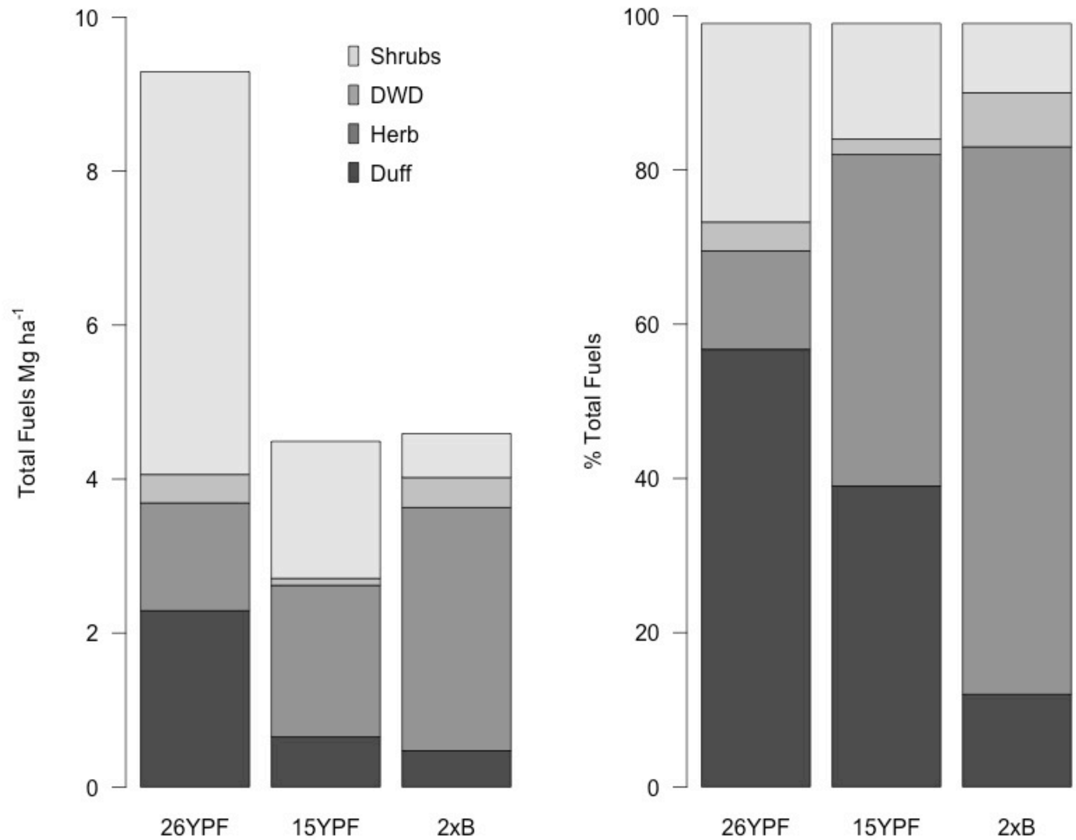

Figure 3.3. (Left) Fuel loads (Mg ha^{-1}) at in *Artemisia tridentata* ssp. *tridentata* plots John Day Fossil Beds, Sheep Rock Unit, for plots with various fire histories: twenty six years since fire (26 YPF, *n*=4), fifteen years post fire (15YPF, *n*=3), and twice burned (both 15 and 26 years ago; 2xB, *n*=5). (Right) Relative fuel loads (Shrub fuel, downed woody debris (DWD), Herbaceous fuels (live and dead grass and forbs) and Duff fuels (including detached shrub leaves and bryophytic material), at John Day Fossil Beds, for plots with various fire histories: twenty six years post fire (26 YPF, *n*=4), fifteen years post fire (15YPF, *n*=3), and twice burned (2xB, *n*=5).

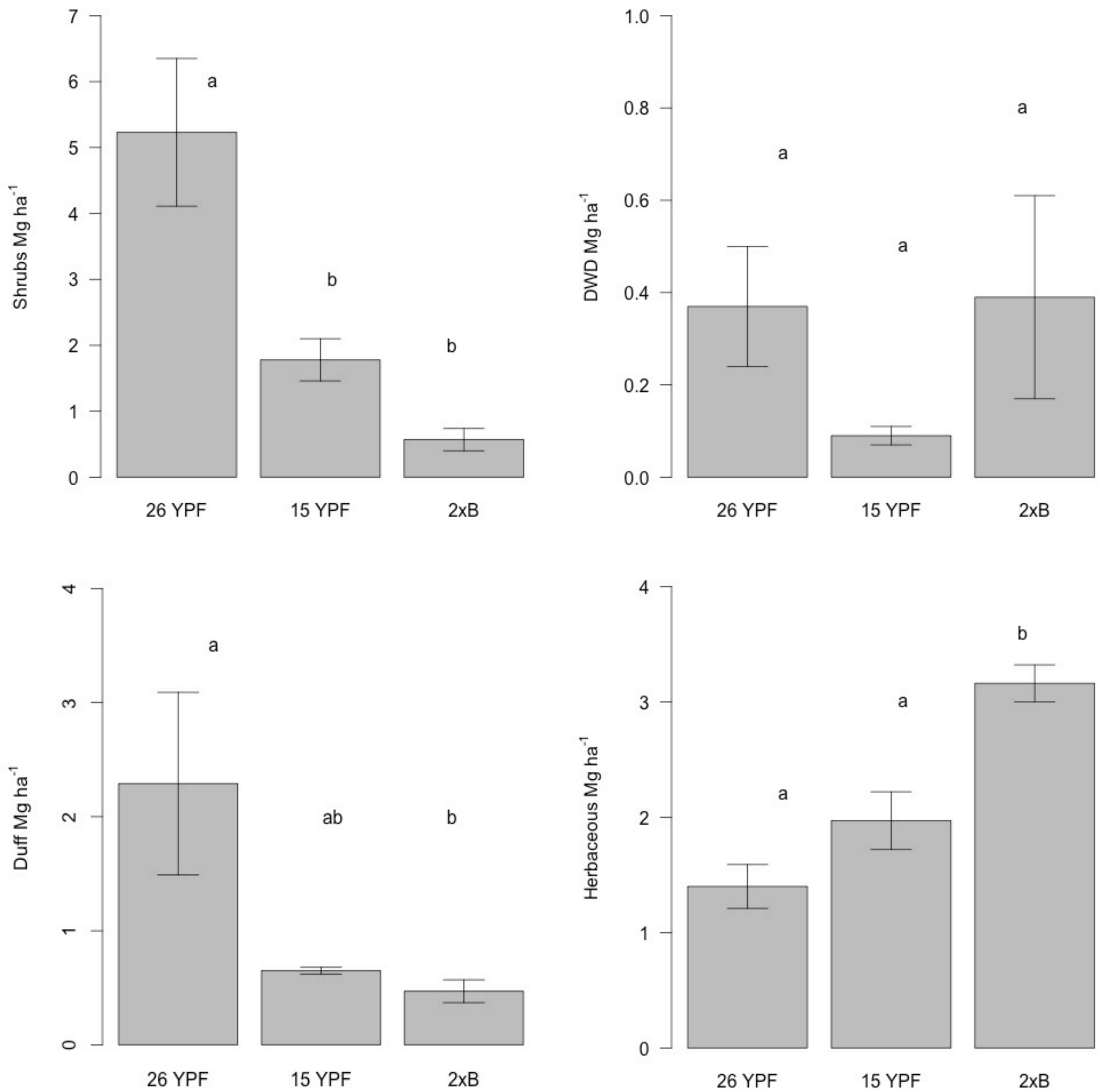

Figure 3.4. Fuel loads by category in *Artemisia tridentata* ssp. *tridentata* plots for all three fire histories (26 years post fire [YPF], 15 YPF, and twice burned [2xB]) at John Day Fossil Beds, Sheep Rock Unit. Error bar shows one standard error. Same letters over bars signifies no significant difference in fuels loads.

CHAPTER 4: CONCLUSION TO THE THESIS, AND FUTURE RESEARCH

This research was conducted to address several specific objectives *1*) to develop a better understanding of how fuel loads and composition change over long periods of time (>10 years) in several sagebrush dominated ecosystems by re-measuring locations of previous fire-effects studies, where pre-fire and immediate post-fire data exists. *2)* The second objective of this research was to understand how repeated burns affect fuels succession. This was accomplished by re-measuring a series of plots at John Day Fossil Beds with three fire histories: burned once 26 years prior, burned once 15 years prior, and twice burned, 26 *and* 15 years prior. *3)* The third objective of this research was to further the collective understanding of fuel loadings and composition in basin big sagebrush (*Artemisia tridentata* spp. *tridentata)* communities where previous research has been limited. This was accomplished by re-sampling two previous basin big sagebrush fire effects studies at John Day Fossil Beds, and Bear Creek, OR.

The data from this study- rates of fuels accumulation, and composition and structure of fuels across time periods, can be used, and was specifically gathered to be used for fire behavior modeling. These models of fire behavior will then be used to inform land manager and wildland firefighters how and under what conditions, fire will spread through a given landscape of concern. This information will not just help to maintain the integrity of the ecosystem, but can potentially save lives of wildland firefighters and residences of the sagebrush steppe.

The reductions seen in woody fuels may suggest that repeated burns retard the rate of fuels succession. The fire return intervals in Wyoming big sagebrush is a contentious issue, partially because this more xeric sagebrush community type is not adjacent to forested stands. The fire scars recorded on trees in forested stands adjacent to mountain big sagebrush allows for the calculation of mean fire return intervals in such community types. Such a method is not possible in Wyoming big sagebrush communities. However, comparing fuel loads and potential fire behavior between sagebrush community types, long-term post-fire, can help develop a better understanding of the historical fire return intervals of xeric sagebrush communities. Understanding the historical fire return interval can be used to inform managers about when resilience post-fire will be greatest in these fragile ecosystems. The increase in time between fire events is at least partially responsible for juniper encroachment in high altitude sagebrush-steppe ecosystems, and the interaction of annual grass invasion and increased fire frequency are the ends and the means of sagebrush ecosystems at relatively low elevations transitioning into states dominated by annual grasses.

Species of concern in the sagebrush steppe rely on a mosaic of different sagebrush community types and seral stages to meet the needs of their complicated life histories. Understanding how these communities respond to fire long-term can be used to manage the landscape matrix in a way to ensure habitat needs will be met at the present and in the future. My research has shown that different sagebrush communities recover at different rates post-fire, have different fuel loads and compositions and should have different potential fire behaviors. I am particularly interested to see if the burned sites from chapter 2 of this thesis will reach 10% sagebrush cover before 2030, as I predicted with the help of sagebrush recovery models from other studies. If that is the case, Wyoming big sagebrush may have a more frequent fire return interval than the current literature suggests, at least at Hart Mountain National Antelope Refuge. If my prediction is correct, determining what factors affect recovery rates in different sagebrush dominated ecosystems will help land managers make informed decisions related to prescribed burns and wildfires. One unique aspect of this research, and potential factor in sagebrush recovery and related fuels recovery rates and dynamics, is that all sites sampled in this study were un-grazed at least since the early 1990s, and the fuels succession post-fire should reflect this fact, but how is unknown. Meta-analysis where my findings are compared to other long-term fuels recovery under different grazing practices will help inform the land owners and land managers on how grazing regimes affects fuels recovery and fire regimes.

This research has provided much needed insight into the dynamics and nuances of long-term fuels recovery in several sagebrush community types, but the potential for this research to inform future research of landscape level fire behavior modeling and long-term habitat management is monumental. Combining this research with other studies of fire effects and sagebrush recovery overtime can lead to eco-regional level comprehension of environmental and man-made factors, potentially affecting management decisions and land use policy. Another way this research could serve potential future research is to help develop a better understanding of how fire behavior, potential plant community shifts and carbon dynamics will change under future climate scenarios.

The findings of this research could seem small is scope, especially compared to the ideas I just proposed: what fuels came back at specific sites, under similar management regimes of no grazing. But this research itself is not supposed answer all questions related to conserving the sagebrush-steppe eco-region. This study was conducted to address specific identified knowledge gaps in our understanding of fire in sagebrush-dominated ecosystems, and to hopefully be incorporated in, and leveraged by future research.

Sagebrush recovery post-fire takes a long time, possibly longer than the careers or even life spans of those who manage it, study it, rely on its ecosystem good and services, or love it for its intrinsic psycho-spiritual value. Even if this research is never combined with fire behavior modeling, or incorporated into a multi state level meta-analysis of sagebrush steppe recovery and carbon dynamics post-fire, there is no doubt that it can be used to inform the managers of Hart Mt. National Antelope Refuge, John day Fossil beds, and the Prineville BLM district on long-term fuels management plans.

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